FINAL REPORT

Review and Development of Life-Cycle Cost (LCC)
and Network Analysis Procedures for NYSDOT
Highway Pavements

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Review and Development of Life-Cycle-Cost (LCC) and Network Analysis Procedures for NYSDOT Highway Pavements

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PART A

A. Evaluation and Recommendations on NYSDOT Network-Level Life Cycle Cost (LCC) Analysis Procedures

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1. INTRODUCTION

1.1 A STUDY PERSPECTIVE

The purpose of this project is to review and develop improved life-cycle-cost (LCC) analysis procedures and network (program) analysis procedures for New York State Department of Transportation (NYSDOT). A review by the research team of NYSDOT procedures indicates that there are areas that could be improved. These areas include:

(a) establishment of optimal goals, optimal budget allocations, and optimal maintenance and rehabilitation (repair) strategies at network-level,

(b) optimal project selection procedures at network-level, and

(c) optimal treatment selection procedure at project-level.

After carefully reviewing these procedures and comparing them to those used by other agencies, the research team will propose improvements for consideration. These proposed improvements will be made in a series of five reports in response to the first five tasks listed below. Upon approval by NYSDOT, these proposals will be put together, constituting a Final Report and a Users Manual.

1.2 AN OVERVIEW OF PAVEMENT MANAGEMENT SYSTEMS

The *AASHTO Guidelines for Pavement Management Systems (1990)*[2] quotes the *Federal Highway Administration's* definition of a Pavement Management System (PMS) as "a set of tools or methods that (can) assist decision makers in finding cost-effective strategies for providing, evaluating and maintaining pavements in a serviceable condition". These *Guidelines*[2] also identify the major requirements for a PMS as being a *Database*, an *Analysis Procedure*, and a *Feedback Process*. NYSDOT has a PMS in operation and most of these requirements for a PMS are already in place, as discussed below. The objective of this study is to determine areas of improvements in the NYSDOT PMS, and make recommendations for these improvements.

Database

A database of pavement inventory, condition, construction and repair history, cost and traffic volume is essential to any PMS. NYSDOT keeps records of most of these data. A report

responding to Task 3 will look at some aspects of these data and recommend improvements in record keeping and, if need be, additional data.

Analysis Procedures

Using data from the database, a PMS can evaluate current (and, preferably predict future) pavement condition or performance. Based on the current (and sometimes predicted) pavement conditions, we can use an analysis procedure to determine most cost effective repair strategies. There are three main types of analysis procedures. These are:

Pavement Condition Analysis in which only current pavement conditions are used to rank and select projects. In case of budget limitations those projects falling far below the assigned rank are deferred to the next budget year when the process is repeated.

Priority Assessment Methods (also known as "bottom-up" methods) first determine the most optimal (based on life-cycle costs) repair actions for each individual project. A variety of methods (including cost/benefit, incremental cost/benefit, cost effectiveness, etc.) are then used to prioritize these projects at the network-level.

Network Optimization Methods (also known as "top-down" methods) first determine optimal network goals, repair strategies or policies, and/or resource requirements by simultaneously evaluating the entire network of pavements. These strategies are then applied to individual projects on which site-specific treatments may be identified.

The current NYSDOT network analysis method is essentially a *Priority Assessment Method*. The procedure, known as Infrastructure Needs Assessment Model (INAM),[3,4,5,6,7] essentially keeps track of all costs and selects projects based on needs and budget constraints. INAM is further discussed in Section 2.2 of this report. The research team is proposing to introduce optimization routines to enhance the capabilities of NYSDOT network-level PMS. The proposed improvements are presented in Section 3.

Feedback Process

A feedback process is essential to a PMS if it is to be reliable. Most of the information used to make current and future decisions need to be verified and/or modified over time. This information may include repair cost data, pavement performance prediction, effects of repair method to pavement deterioration, and recommended versus applied treatments. The feedback process used by NYSDOT will be evaluated and strengthened in the process of responding to Tasks 2, 3, and 4.

1.3 NETWORK-LEVEL VERSUS PROJECT-LEVEL PAVEMENT MANAGEMENT

Before discussing and evaluating the current network-level and project-level pavement management system used by NYSDOT, it is important to define what network-level and project-level pavement management consist of within the framework of a pavement management system.

Network-Level Pavement Management

Network (program)-level pavement management takes into consideration all pavements in the agency network. At this level the main objective is to establish network-level policies, budget requirements, repair priorities and schedules. *The AASHTO Guidelines for Pavement Management Systems (1990)*[2] identifies specific products required to meet the objectives of a network-level PMS as:

- Information concerning the condition or health of the pavement network.
- Establishment of maintenance, rehabilitation and reconstruction policies.
- Estimation of budget requirements.
- Determination of network priorities.

The results of network-level analysis are of great interest to elected officials, budget directors, and managers of the agency.

Project-Level Pavement Management

Project-level pavement management determines the optimal treatment strategy for maintaining a specific segment of pavement in the network. This level of management involves assessing

causes of pavement deterioration, determining potential solutions, assessing benefits of alternatives, and selecting a solution and design. Detailed site-specific data on pavement condition, materials etc., are required at this level of decision making.

Generally, in a "top down" pavement management system, network-level analysis is done first, followed by project-level analysis. The project-level analysis essentially implements network-level strategies, observes budget restrictions and network priorities. In such a system, network preservation and performance take precedence over the life-cycle-cost of preserving individual projects. This means network goals and policies guide project selection and treatment selection.

NYSDOT Pavement Management

NYSDOT has both network-level and project-level pavement management. The system generally recognizes the "top down" procedure. However, there is a need to bring closer the project-level and network-level analyses such that network-level strategies drive project-level analysis and not vice versa. To accomplish this, we propose improvements in NYSDOT's network-level analysis procedures in order to facilitate the determination of optimal budget and repair policies, the evaluation of consequences of resource constraints on network performance, and the determination of network priorities. The current project-level analysis will be evaluated and recommendations will be made as to how it can be driven by results of network-level analysis. This means that network-level analysis sets up maintenance, rehabilitation and reconstruction policies (or strategies) and the project-level analysis determines the best treatment for a project that lies within a specified strategy.

1.4 SUMMARY OF THE CONTENTS OF THIS REPORT

This report constitutes a response to the Task 1 namely: *To review, compare, and evaluate project-level and network-level pavement life-cycle cost analysis procedures in use by the Department and other highway agencies.* Section 2 presents a summary of a survey of pavement management systems used by agencies in the USA and in Canada. This Section also summarizes the method used by NYSDOT, and proposes improvements to the existing system. Section 3 presents proposals for improving network-level analysis procedures for NYSDOT. Section 4

discusses the current NYSDOT project-level analysis and makes recommendations for improvements. Finally, Section 5 presents the conclusions of the Task-1 report.

2. A SURVEY OF PAVEMENT MANAGEMENT SYSTEMS

In Section 1.2 it was stated that a good pavement management system needs a *database*, an *analysis method(s)* and a *feedback process.* The main distinguishing factor of pavement management systems used by agencies in the USA and in Canada is the type of analysis method used. Consequently, this survey will categorize agencies based on this factor. Another distinguishing factor that is related to the *analysis method* is the order in which the analysis is done. The first is a *"bottom up"* approach whereby treatments for individual projects are selected first followed by project selection at network-level. The second is a *"top down"* approach where network-level goals, strategies and budgets are determined first, followed by a simultaneous project and treatment selection process that is guided by network-level priorities.

2.1 CURRENT PROJECT AND TREATMENT SELECTION PRACTICES

Project and treatment selection practices form the core of pavement management systems. Highway agencies use these practices to control long-term network conditions and budget levels. In this section we present an overview of project and treatment selection practices by highway agencies in the USA and in Canada. Most of the results contained in this section are based on results of a survey of project and treatment selection methodologies conducted by the *National Cooperative Highway Research Program (NCHRP) Synthesis 222* [8].

Project Selection

The process of project identification and selection can take place at different stages. It can take place before the budget is set, in which case project selection becomes the basis for establishing required budget needs. Alternatively, project selection can be part of the budget setting process. *NCHRP Synthesis 222*[3] shows that the most common approach (57% of agencies in the USA and in Canada) do project selection after the budget setting process. There are different methods of project selection. The *AASHTO Guidelines for Pavement Management Systems*[2] identify three

main project selection methods as *Pavement Condition Analysis, Priority Assessment Models, and Network Optimization Models*. These methods are briefly discussed in Section 1.2. However, other methods are also in use as reported in *NCHRP Synthesis 222*[8]. According to this synthesis, which presents results of a survey of 46 highway agencies in the USA and 10 in Canadian provinces, the majority of agencies use *Pavement Condition Analysis* (47%), followed by *Network Optimization Models* (19%), and *Priority Assessment Models* (16%). The rest of the agencies use systemic or other methods (21%). Figure A- 2.1 shows this distribution of analysis methods among agencies.

Agencies that use *Priority Assessment Methods* prioritize their projects over a planning horizon. About 52% of these agencies use a pavement condition ranking method to prioritize projects, 21% use cost/benefit or incremental cost/benefit methods, while 11% use a life-cycle costing method.

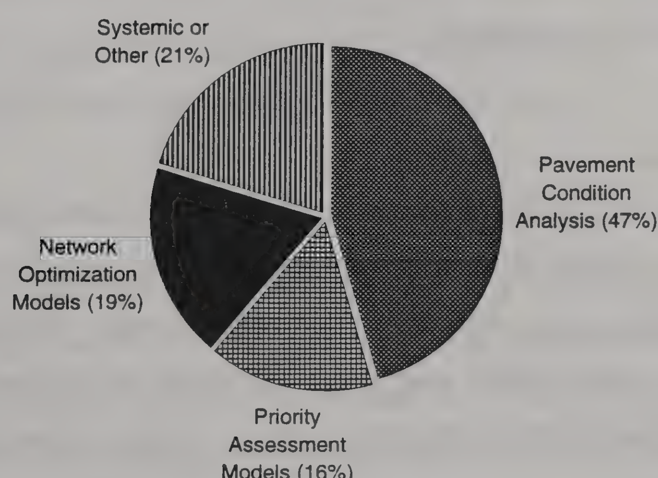

Figure A- 2.1 Project Selection Methods used in the USA and in Canada

Agencies that use *Network Optimization Methods* for project selection employ a variety of methods to do this. These methods include linear programming, non-linear programming, integer programming, dynamic programming, heuristic and other cost/benefit methods. *NCHRP Synthesis 222*[8] shows that the majority of these agencies use linear programming (62%), followed by other methods as shown in Figure A- 2.2.

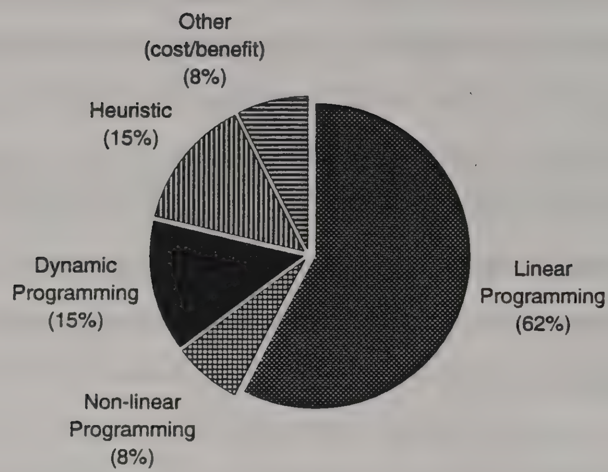

Figure A- 2.2 Network Optimization Methods used in the USA and in Canada

In using optimization methods for network-level analysis, two most commonly used constraints are limits on budget levels and limits on overall network condition. At the project level, three factors are commonly used in decision making. These are design service life, project cost and benefits provided by the treatments.

Value of Projects

Project selection involves the prioritizing and ranking candidate projects in order of their worth. The majority of agencies in the USA and in Canada use reductions in pavement distress and roughness to value projects and their respective treatments. Other measures used to a lesser extent include rut depth, project cost, project design service life, surface friction. Few agencies indicated direct use of project benefits, such as savings in user costs, agency costs, safety improvements, etc.

Treatment Selection

A majority of agencies indicate that they use multiple treatments in their pavement management systems. However, most agencies use between one and four and very few use more than seven alternative treatments, as shown in Figure A- 2.3. Treatment selection most commonly takes place as part of project selection process (56% of agencies). Forty-one percent of agencies select treatments after projects selection, and a minority of agencies indicated that they select

treatments before project selection. The most commonly used factors in selecting treatments include current pavement condition, traffic loading, total treatment cost, design service life, functional classification of pavements, and pavement surface type. Life-cycle cost is used to a lesser extent in treatment selection.

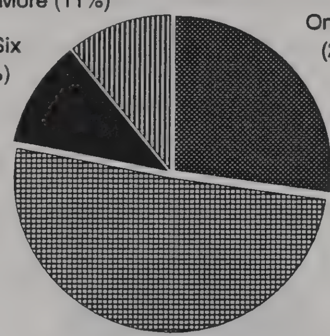

Figure A- 2.3 Number of Alternative Treatments per Project
(for the USA and Canadian Highway Agencies)

Analysis Period

With the exception of agencies that select projects using the *Pavement Condition Analysis Method*, the remaining agencies consider multiple years in their project and treatment selection process. The majority of these agencies use 3-5 years and 6-10 year analysis periods. Figure A-2.4 shows the distribution of analysis periods used by agencies in the USA and in Canada.

Factors Influencing Project and Treatment Selection

Regardless of the methods used in project and treatment selection, there are some factors that are common to all these methods that influence the process. These factors need to be considered when a system is evaluated and/or improved. *NCHRP Synthesis 222*[8] identifies nine such factors as:

- Geographic boundaries and the balance of work between districts.

- Political influence or citizen requests.
- Combination with other types of projects for program development.
- Influence or bias of individual developing the program.
- Geometric constraints.
- In-house design capabilities.
- Traffic operations and safety upgrading.
- Locally available resources.
- Policies and mandates.

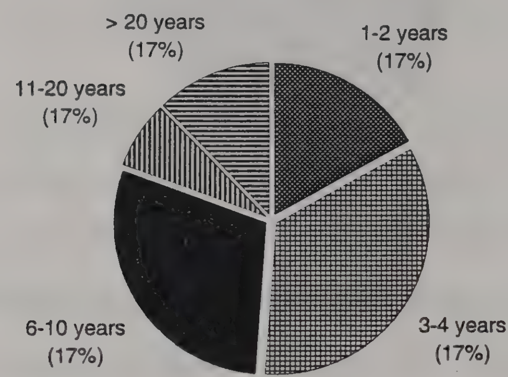

Figure A- 2.4 Analysis Periods for Project and Treatment Selection
(for the USA and Canadian Highway Agencies)

A pavement management system must be aware of such factors so as to improve them or take them into consideration when developing strategies at program or project development levels.

2.2 NYSDOT Project and Treatment Selection Practice

Background and Historical Perspective

Central to the NYSDOT project selection process is a model called *Infrastructure Needs Assessment Model* (INAM)[3,4]. According to Brunso [3], INAM grew out of the Highway Condition Projection Model (HCPM) developed by David T. Hartgen and his staff at NYSDOT

in the early 1980's. Within the next few years a bridge model, using similar concepts of repair work and performance, was developed in the Planning Division of the NYSDOT. A number of micro-computer models were tested to do the bookkeeping of repair strategies, of costs, and of performance measures for highways, as well as bridges. The Planning Division finally decided to develop a single model that would incorporate the HCPM and the bridge model with most useful features of earlier models. A task force was appointed with representatives from the NYSDOT Planning and Research Bureau and the Data Services Bureau. Staff from the Main Office in Albany and from regional offices were interviewed to determine which features would be most useful to them. A consensus emerged to develop a model that would have the following minimum characteristics:

1. User could predict pavement and bridge conditions for at least 20 years.
2. User could select for analysis a highway or bridge subsystem by region, county, federal aid system.
3. User could specify budget constraints.
4. User could determine and/or specify locations where highway or bridge work would occur.
5. User could produce a 5-year program of highway and bridge projects.
6. The model would be user-friendly.

Project and Treatment Selection

Geoffroy and Shufon[4] have presented an excellent account of the project and treatment selection procedures used by NYSDOT. It shows how the NYSDOT Main Office in Albany interacts with the eleven regions in coming up with five-year programs of highway maintenance, which include pavement maintenance, rehabilitation, and non-pavement maintenance work. The paper reports that more than a third of the 15,000 road miles of the state highway system were constructed during the Interstate 'build era'. Many of these facilities are now reaching the end of their service life. In January 1989 a comprehensive plan was released to provide a method for selecting actions that will achieve a set of strategic goals. The Main Office is responsible for developing policies, establishing goals, allocating funds to the regions and monitoring accomplishments. Funds are provided to the Main Office in two separate allocations: (a) operating funds which

finance salaries, equipment, and some materials for pavement repair work that is done by NYSDOT forces, and (b) a capital allocation that funds work to be done through competitive bid contracts. Resources are allocated to the regions in a similar way. The day-to-day pavement maintenance activities are performed by highway maintenance personnel in 65 field offices called residences. Residence boundaries are generally the same as county lines. NYSDOT procedures to evaluate and select treatments are outlined in various manuals and reports.[9,10,11,12]

The Main Office, in coordination with regional offices, comes up with goals to be achieved in the form of desirable pavement conditions at network-level. Given the budget allocations and pavement goals, each regional office develops a comprehensive five-year program of pavement projects. The network pavement-survey data, collected annually, are used to measure the impact of program implementation on pavement condition which in turn provides a feedback for goals of subsequent years.

Since 1981, NYSDOT has used a windshield survey methodology to assess pavement conditions. The method uses photographic scales that show the condition of pavements at various stages of deterioration. The outcome of this survey is a *Pavement Surface Rating Score* ranging from 1 to 10 (10 being the best). In 1990 the survey method was enhanced. It now enables each highway section to be classified into one of five general treatment categories:

Do-nothing,

Preventive maintenance,

Corrective maintenance,

Rehabilitation,

Major rehabilitation/Reconstruction.

The photographic scales, one for each pavement type, were constructed so that each one of the scale points represents a pavement requiring one of the general treatments. Tables 2.1 and 2.2 show the treatment types recommended for each condition-state and pavement type.

Table A-2.1 Network-Level Distress Treatment

Treatment Strategy	Code	Pavement Type		
		Rigid	Flexible	Overlay
Do Nothing	1	-----------	-----------	-----------
Preventive Maintenance	2	Reseal Joints	Fill Cracks	Fill Cracks
Preventive Maintenance (High Cost)	3	Reseal Joints & Patch	Fill Cracks & Patch	Fill Cracks & Patch
Preventive Maintenance (Paving)	4	-----------	1½" Asphalt Concrete Overlay	1½" Asphalt Concrete Overlay
Corrective Maintenance	4	Reseal Joints Patch & Grind	-----------	-----------
Corrective Maintenance (High Cost)	5	-----------	Mill, Patch, 1½" Asphalt Concrete Overlay	Mill, Patch, 1½" Asphalt Concrete Overlay
Rehabilitation	6	4" Asphalt Concrete Overlay	2½" Asphalt Concrete Overlay	2½" Asphalt Concrete Overlay
Rehabilitation (High Cost)	7	5" Asphalt Concrete Overlay	4" Asphalt Concrete Overlay	4" Asphalt Concrete Overlay
Major Rehabilitation	8	Rubblize, 6" Asphalt Concrete or Reconstruct	Reconstruct	Mill, Rubblize, 6" Asphalt Concrete or Reconstruct

Source: The NYSDOT Pavement Condition for New York's Highways: 1994 [14]

The goal-setting process starts with the consideration of the NYSDOT mission, state transportation requirements, anticipated resource levels in support of each element of the system and the condition (existing and historical) of the transportation system. The goals are then released to the regions during the early fall for use in updating the 5-year Program. Typically, the pavement goal focuses on reducing the number of lane-miles of pavement rated poor (surface score = 5) and fair (surface score = 6) during the annual pavement condition survey. In 1991, the

regional goal statements were expanded to include a measure that ensures that priority is given to high traffic volume facilities.

Table A-2.2 Surface Rating Scale

Scale Points	Condition Rating	Distress Frequency	Distress Severity	Treatment Categories Assigned
10	Excellent	None	None	Do Nothing
9	Excellent	None	None	Do Nothing
8	Good	Infrequent	Very slight	Preventive Maintenance
7	Good	Infrequent to Occasional	Slight	Preventive Maintenance (High Cost) Preventive Maintenance (Paving)
6	Fair	Occasional to Frequent	Slight to Moderate	Preventive Maintenance (Paving) or Corrective Maintenance (High Cost) or Rehabilitation
5	Poor	Occasional to Frequent	Moderate to Severe	Rehabilitation or Rehabilitation (High Cost)
4	Poor	Frequent	Severe	Rehabilitation (High Cost) or Major Rehabilitation
1 - 3	Poor	Very Frequent	Very Severe	Major Rehabilitation

Source: The NYSDOT Pavement Condition for New York's Highways: 1994 [14]

This, in a sense, takes user costs into consideration implicitly. As discussed in Section 2.1, many agencies do not consider user cost during network-level investment planning. Other factors influencing treatment selection include traffic volume and dominant distress as described by the 1994 report on NYSDOT pavement conditions.[14] Treatment selection process is done at another level of analysis besides INAM known as project-level life-cycle cost analysis. NYSDOT

Pavement Rehabilitation Manual, Volume II [10] outlines the method used to select treatments. This process is based on the life-cycle cost of projects which means each selected treatment represents the most cost-effective way of preserving the pavement over its life time.

The NYSDOT system leaves the responsibilities of project development, and of maintenance and rehabilitation programs to regional offices. Many factors go into the determination of candidate projects. These factors vary from safety consideration to factors such as corridors of statewide significance, economic development and citizen complaints. INAM is then used to assist each regional program committee in selecting projects that will best achieve the specified goals. INAM calculates the cost of a user-specified pavement program and predicts its impact on the network condition. The program that meets the goals and satisfies local considerations is presented to the Main Office for approval. In this way the system allows regional flexibility in selecting a program, as long as it satisfies statewide network goals.

Central to INAM are the pavement performance prediction models. NYSDOT has network-level performance prediction models for different types of pavements. These models are regression equations of the form:

$$PSR(y) = 10 - \alpha\sqrt{y}$$

where: α is a constant depending on pavement type and treatment

y is the number of years since the pavement was in condition scale 10.

These models are developed for each region. A report by this research team responding to Task-2 will discuss in detail these performance prediction models and will recommend improvements.

2.3 SUMMARY

Section 2 of this report presents the current state-of-practice in pavement management. It outlines several methods used by agencies in the USA and in Canada for project and treatment selection. The section then looks at current system used by NYSDOT. The system first selects treatments based on pavement condition, traffic and dominant distress before project formation and selection. Network goals and budgets are set independent of the projects and then INAM is

used to select projects. INAM is a network-level project selection model. Its main task is to do the bookkeeping of all repair work, deferred maintenance work, repair cost, average condition of infrastructure, etc., over the 5-year planning horizon. This method would fall under the *Priority Assessment Models* described in Section 1.2. It is not an optimization model.

In Sections 3.0 and 4.0, we propose a "top down" approach to project selection and treatment selection process. The network-level analysis procedure employs optimization models to come up with optimal goals, repair strategies, and budget levels. This process involves simultaneous project and treatment selection such that the network goals are met.

3 PROPOSED NETWORK-LEVEL PROCEDURE FOR NYSDOT

This section proposes a network optimization procedure which can be used to set network goals, priorities, policies and budget requirements at state level and select projects and treatments at the regional level. The models are based on a Markov Decision Process (MDP).[15] The method considers pavement performance over time as a stochastic process and determines long-term and short-term treatment policies as well as network priorities and optimal budget levels. Task-2 Report [16] discusses in detail the modeling of pavement performance as a Markov process.

3.1 Pavement Categorization

Throughout this section a state will imply a pavement surface rating score for a highway pavement. Therefore, the set of states is identified as $S = \{s: s = 1,2,3,....,10\}$. Other sets include: set $A = \{a: a = 1,2,3,....,8\}$, defined as a set of all treatment (action) categories used by NYSDOT; a set of pavement categories $I = \{i: i = 1,2,3,....,I\}$; a set of regions $R = \{r: r = 1,2,3,....,11\}$, and a set of traffic-volume categories $T = \{t: t = 1,2,3,....,T\}$.

The following is an outline of factors that are used to describe repair policy variables which are used in the optimization models. The policy variables in the long-term model (Z_{trisa}) and the

short-term model $\left(X_{trisa}^{(y)}\right)$ represent the total length (in lane-miles) of state highway pavements in specific pavement categories. Z_{trisa} represent the long-term number of lane-miles carrying traffic volume category *t*, in region *r*, of pavement category *i* that will be in state *s* and treatment (action) *a* is applied. $X_{trisa}^{(y)}$ are short-term variables that are defined, for every year (*y*) of the planning period (say, 5 years), in a similar manner as the long-term variable Z_{trisa}. All pavement sections are categorized and aggregated in lane-miles of similar categories. The factors used to specify policy variables are:

1. Region (11 regions in the NY state);
2. Pavement type (flexible, overlaid, rigid);
3. Expected traffic loading (high, low);
4. Pavement strength (high, low);
5. Pavement surface distress or condition (10 surface score levels);
6. Traffic volume;
7. Treatment category.

Categorization by Region

Since NYSDOT regions have autonomy in defining and selecting projects, the long-run and short-run maintenance policies $\left(Z_{trisa} \text{ and } X_{trisa}^{(y)}\right)$ are specified by regions (r). These policy variables will specify what has to be achieved by each region in order to meet network goals. These region-specific policies can also be used as a rational way of allocating resources among regions.

Table A-3.1 Description of Repair Actions *(a)* Related to the Three Pavement Types.

Code	1	2	3	4	5	6	7	8
Repair Action / Pavement Type	Do Nothing	Preventive Maintenance	Preventive Maintenance (High Cost)	Corrective Maintenance (Rigid) Preventive Maintenance-Paving (Flexible & Overlaid)	Corrective Maintenance (High Cost)	Rehabilitation	Rehabilitation (High Cost)	Major Rehabilitation/ Reconstruction
RIGID	Do Nothing	Clean, Seal Fill Joints/Cracks	Clean, Seal Fill Joints/Cracks Prepare & Repair Spalls	Clean, Seal Fill Joints/Cracks Prepare & Repair Spalls, Partial Slab Grinding/ Texturing		4" ACC Overlay 3" ACC Shoulders	5" ACC overlay 3" ACC Shoulders	9" PCC Paving 3" Rigid Shoulders
						All of Corrective Maintenance + Excavation, Tack Coat, True & Level, Type 3 Binder, Type 6F Top, Saw & Seal Overlay, Drainage, Curbing, Guide Rail, Signage, Landscape, Stripping.	All of Corrective Maintenance + Excavation, Tack Coat, True & Level, Type 3 Binder, Type 6F Top, Saw & Seal Overlay, Drainage, Curbing, Guide Rail, Signage, Landscape, Stripping.	Pavement Removal, Excavation, Subbase Items, Class C Reinforced PCCP, Drainage, Curbing, Guide Rail, Signage, Landscape, Stripping.
OVERLAID	Do Nothing	Clean, Seal Fill Joints/Cracks	Clean, Seal Fill Joints/Cracks Type 6F Top	1.5" ACC Armor Coat, &1.5" ACC Shoulders	1.5" ACC Armor Coat, &1.5" ACC Shoulders	2.5" ACC Overlay, & 2.5" Shoulders	4" ACC Overlay, & 3" Shoulders	Rubblize Existing Pavement, 6" Overlay, & 3" shlds
				Clean, Seal Fill Joints/Cracks Excavation, Clean Pavement, True & Level, Type 6F Top	Clean, Seal Fill Joints/Cracks Excavation, Cold Milling, Clean Pavement, Type 6F Top	Excavation, Clean Pavement, True & Level, Type 3 Binder, Type 6F Top, Drainage, Guide Rail, Curbing, Landscaping, Signage, Stripping	Excavation, Clean Pavement, True & Level, Type 3 Binder, Type 6F Top, Drainage, Guide Rail, Curbing, Landscaping, Signage, Stripping	Type 3 Binder, Type 6F Top, Drainage, Guide Rail, Curbing, Landscaping, Signage, Stripping
FLEXIBLE	Do Nothing	Same as for Overlaid Pavements Above	Same as for Overlaid Pavements Above	Same as for Overlaid Pavements Above	Same as for Overlaid Pavements Above	Same as for Overlaid Pavements Above	Same as for Overlaid Pavements Above	10.5" ACCP, 3" Shoulders,
								Excavate, Remove Pavement, Type 1 Base, Type 3 Binder, Type 6F Top, Roadside Work as for Overlaid Pavements Above

Source: 1994 INAM Users Manual [6]

Categorization by Pavement Type

Pavement deterioration rates and the type of treatment *(a)* to be applied on a pavement depend on the type of pavement. Pavement type refers to the pavement surface type (flexible, overlaid, and rigid). Task-2 Report of this research project shows how pavement performance differ among the different types of pavements. In this report it suffices to say that pavement type is an important factor in categorizing pavements.

Categorization by Expected Traffic Loading

Traffic loading refers to the number of the AASHTO "*equivalent standard axle loads*" (ESAL) applied daily. Since this information is not easy to get, we can use the daily traffic volume of heavy vehicles (mainly, volume of trucks) to categorize pavements. Task-2 Report shows that pavement deterioration differs among pavements with high and low heavy traffic volume. Therefore, truck traffic will be used in categorizing pavements.

Categorization by Pavement Strength

Pavements of a similar surface type (say flexible), will deteriorate differently if their thickness and the type and strength of underlying layers (base and/or sub-base) are different. Again, Task-2 Report demonstrates these differences. This factor is going to be used in categorizing pavements. The three factors: pavement type, traffic loading, and pavement strength, are the major factors in determining the performance of highway pavements. Consequently, a single letter *i*, is used to denote the 12 combinations of these three factors in the aggregation process and in the policies $\left(X_{trisa}^{(y)} \quad and \quad Z_{trisa}\right)$.

Categorization by Pavement Surface Distress or Condition

The measure of pavement performance is surface distress expressed on a surface rating scale of 1 - 10, 10 being the best. The surface rating score of a pavement section is denoted as a "state (*s*)". The transition of a pavement from one state to another constitutes its performance over time and is modeled as a stochastic (Markov) process. Task-2 Report gives a detailed description of these states and their progression over time in terms of transition probabilities.

Categorization by Traffic Volume

It is important to categorize highway pavements in terms of their daily traffic volume *(t)* if user cost (vehicle operating cost) is going to be a factor in the formulation of long-term and short-term repair policies. It is proposed to categorize pavements in terms of 30 traffic volume categories in vpd/lane: from 0 - 1,000 to 29,001 - 30,000. It is also possible to use smaller intervals of say 500 vpd/lane and have 60 traffic volume categories. This will make the problems larger but they will still be solvable.

Categorization by Treatment Types (Action)

While the type of repair action *(a)* applied to a pavement is not a factor in categorizing pavements, it is central to both long-term and short-term policies and the project selection phase. The INAM User Manual (1994)[6] specifies 8 treatment categories per pavement type. These are:

1. Do Nothing,
2. Preventive Maintenance,
3. Preventive Maintenance (high cost),
4. Corrective Maintenance,
5. Corrective Maintenance (high cost),
6. Rehabilitation,
7. Rehabilitation (high cost),
8. Major Rehabilitation / Reconstruction.

Table 3.1 presents a description of these repair actions for each of the three pavement types.

3.2 Pavement Performance Prediction

Prediction of pavement performance is essential in a multi-year network optimization system. There are many methods of modeling pavement performance. These vary from regression models to neural network models to probabilistic models, like Markov or semi-Markov models. Depending on the decision support system used one method may be preferred to another. The proposed decision support system is based on the Markov Decision Process (MDP).[15] This system uses transition probabilities to predict pavement performance over time. A transition

probability P_{isak} is the probability that a section of pavement category i currently in state s will change to state k in the next year if treatment a is applied now. In MDP these transition probabilities are assumed to be stable over time while in the semi-MDP the transition probabilities are allowed to change over the lifetime of specific pavements. We will use transition probabilities in the development of the proposed decision support system. The plausibility of the Markovian assumptions in modeling highway pavement performance is discussed in Task-2 Report. Task-2 Report will also survey the current practices in modeling and predicting pavement condition. Some of the recent survey results of pavement performance prediction can be seen in NCHRP Synthesis 203.[17]

3.3 AGENCY COST

Pavement maintenance and rehabilitation costs vary a lot among different agencies in the country and among different regions of an agency. A good PMS needs a reliable method of estimating agency repair (maintenance and capital) costs for various repair strategies. These estimates should relate repair costs to variables such as pavement type (e.g., rigid, overlaid, or flexible), pavement condition (distress or roughness level), and project location (region). This research team will evaluate NYSDOT's capability to estimate agency cost and make recommendation for improvements in response to Task 4, as described in the introduction to this report. We stress the need for agency cost estimates to be related to pavement condition for optimal network-level strategies. An example of a study that relates agency cost to pavement condition was done for the U. S. Army Construction Research Laboratory (CERL) by Sharaf et al.[18] The results of this study are summarized below.

U. S. Army CERL Agency Costs

Sharaf et al.[18] compiled cost data for flexible and overlay pavements under the management of the U. S. Army Construction Engineering Research Laboratory (CERL). They categorized agency cost into "repair" (capital) cost (which is the initial cost of doing a major rehabilitation work on pavement surface) and routine maintenance cost. Capital cost was further categorized into fixed and variable costs. Fixed capital cost is the cost of applying a particular repair

technique on an already prepared surface. This cost depends only on the type of repair work. Variable cost, on the other hand, is the surface preparation cost. This is the cost of preparing a damaged pavement surface so that it is ready for any repair action. Variable repair cost depends on pavement surface condition only - the better the surface condition, the less the variable capital cost. The work by Sharaf et al. was published in 1987, which makes the cost estimates rather outdated. However, the purpose of reviewing this work is to get an idea of how to present agency cost as it varies with pavement condition. The types of treatment categories whose data are reported in Sharaf's paper include:

- Routine or preventive maintenance
- Corrective maintenance (Surface treatment)
- Rehabilitation (Thin overlay)
- Rehabilitation - high cost (Thick overlay)
- Major Rehabilitation or Reconstruction.

In their paper, Sharaf et al.[18] used the CERL's Pavement Condition Index (PCI) scale to represent pavement condition. In this scale "100" represent an excellent (as new) pavement while "0" means very poor surface condition. This scale is similar to the NYSDOT surface condition rating in that they both measure pavement distress. The CERL repair costs reported by Sharaf et al.[18] are summarized in Tables 3.2, 3.3, and 3.4. Total repair (capital) cost is the sum of fixed and variable costs. Table 6.5 presents a summary of these costs.

Table A-3.2 Fixed Repair (Capital) Costs (Dollars/square yard or $/sy)

Activities	Corrective maintenance	Rehabilitation (Thin overlay)	Rehab.(high cost) (Thick overlay)	Reconstruction
Unit cost	1.58	3.76	5.07	20.70

Adapted form Sharaf et al.[18]

Table A-3.3 Variable Repair (Capital Cost ($/sy)

PCI range	0 - 20	21 - 40	41 - 60	61 - 80	81 - 100
Unit cost	18.50	8.50	5.20	0.51	0.15

Adapted from Sharaf et al.[18]

Table A-3.4 CERL Average Agency Costs for Asphalt and Overlaid Pavements (1987 $/sq.yd.

Activity \ PCI	0 - 20	21 - 40	41 - 60	61 - 80	81 - 100
Do-nothing	0.00	0.00	0.00	0.00	0.00
Preventive Maintenance	5.78	1.63	0.69	0.37	0.10
Corrective maintenance	21.17	11.17	7.87	3.18	2.82
Rehabilitation	23.57	13.57	10.27	5.58	5.22
Reconstruction	39.20	29.20	25.90	21.21	20.85

Adapted from Sharaf et al.[18]

NYSDOT Agency Cost

We will use NYSDOT's agency cost estimates in the network-level (program) analysis procedure. This means we need to develop reliable estimates of agency costs for various treatment strategies, pavement conditions, pavement types, and regions. Thus, the agency or repair cost, (referred to as AC_{risa} in the models in Sections 3.5 and 3.6) will have to be categorized by region *r*, pavement type *i*, pavement condition *s*, and treatment type *a*. This task of estimating agency cost will be accomplished in response to Task 4 of the Scope of Services as described in the introduction of this report. Table 3.5 shows an example of the average contract costs for the treatments listed in Table 3.1. These costs were compiled by Geoffroy and Shufon[2] from NYSDOT's Bid Analysis Management System.

3.4 USER COST

At network (program) analysis level we believe that a PMS ought to set its highway maintenance and rehabilitation strategies taking into consideration total cost to the system. This total cost includes user costs as well as agency costs. Any treatment done on a highway pavement has a direct consequence on user cost which may include vehicle operating cost, vehicle owning cost, and delays. The agency cost, on the other hand, constitutes a very small percentage of the user cost. The *Organization for Economic Co-operation and Development* (OECD)[19] reports that road maintenance cost constitutes only 2% of the total vehicle operating cost in the U. S.

Table A-3.5 Statewide Cost Estimates for Total Contract Cost (in $ '000 per lane-mile)

Treatment Strategy	Lane Configuration*				
	4-D	6-D	2-U	4-U	6-U
Reseal Joints	15	18	15	20	21
Reseal Joints, Patch spalls	16	20	16	21	23
Reseal Joints, Patch spalls, Grind	38	42	38	43	45
4" ACC Overlay, 3" Shoulders	268	249	300	256	241
5" ACC Overlay, 3" Shoulders	304	285	335	291	277
9" PCCP Reconstruction	1456	1424	1496	1429	1407
Fill Cracks	7	9	7	10	11
Fill Cracks, Patch pavement	17	19	17	20	21
1½" ACC armor coat & shoulders	85	75	99	77	69
1½" Overlay, Shldrs, Milling	110	99	123	101	93
2½" Overlay and Shoulders	128	112	148	115	103
4" Overlay and 3" Shoulders	234	210	266	213	196
Rubblize, 6" Overlay, 3" Shoulders	532	508	563	511	494
10½" ACCP Reconstruction	693	669	725	673	655

* D and U denote divided and undivided highways, respectively.
Adapted form Geoffroy and Shufon[2]

However, a slight change in maintenance or rehabilitation expenditure (due to changes in program strategies) can have disproportionately large changes in user costs. We, therefore, recommend that user costs be directly incorporated in the program analysis stage in order to come up with optimal network-level strategies. In responding to Task 5 of this project, the research team will evaluate the Department's capability to estimate user cost. In Task 5, we will also calibrate user cost models for New York State highways based on the World Bank's Vehicle Operating Cost Models[20] and recommendation their use to NYSDOT. An example of the use of World Bank user cost models in PMS is reported by Bein[21] for the Saskatchewan Pavement Maintenance Information System.

For the models presented in Sections 3.5 and 3.6, user cost (UC_{tris}) is specified by traffic volume category *t*, NYSDOT region *r*, pavement type *i*, and pavement surface condition (state) *s*. The region factor, *r,* is included because terrain may change from region to region and this may influence vehicle operating cost.

3.5 LONG-TERM NETWORK GOALS AND REPAIR POLICIES

The proposed decision support system represents a top-down approach to pavement management. The system consists of three phases namely:

- Phase 1: Long-term network-level goals and repair policies (Section 3.5).
- Phase 2: Short-term network-level repair policies (Section 3.6).
- Phase 3: Short-term project selection process (Section 3.7).

In phase 1, long-term strategies are determined for the entire state highway system. These are sustainable steady-state policies that if followed will maintain pavement conditions at an optimal level given the specified resources. This phase can also be used to determine network-level decision factors such as optimal budget levels; optimal network condition; and, given a budget allocation, consequences of reduced budget on network condition as well as user cost.

The long-term model is presented in equations 3.1 to 3.7. The objective is to minimize the sum of agency and user costs, subject to a number of constraints. Constraints may include resources (budget), requirements on desirable minimum or maximum network pavement conditions, etc.

The problem is formulated as a Markov decision process (MDP) and solved as a linear program. Long-term policies are given by the optimal solution to the long-term problem, Z^*_{trisa} (optimal solution to equations 3.1 through 3.7). The policies specify that in the long-run, Z lane-miles of pavements category i, in region r that carry traffic volume category t are expected to be in state s, and will be treated by repair type a. These long-term policies are further used as goals or constraints to be met in phases 2 and 3.

Long-Term Model

Minimize $\sum_t \sum_r \sum_i \sum_s \sum_a Z_{trisa} \left[AC_{risa} + \sum_k UC_{tik} P_{isak} \right]$ 3.1

Subject to:

Conservation of highway network size

$\sum_i \sum_s \sum_a Z_{trisa} = Z_{tr} \qquad \forall\ t, r$ 3.2

Dynamic changes in pavement conditions (Markov process)

$\sum_a Z_{trika} = \sum_s \sum_a Z_{trisa} P_{isak} \qquad \forall\ t, r, i, k$ 3.3

Annual (long-term) total budget allocation

$\sum_t \sum_r \sum_i \sum_s \sum_a Z_{trisa} AC_{risa} \leq B$ 3.4

Network condition specifications (optional)

$\sum_t \sum_r \sum_i \sum_a Z_{trisa} \leq \delta_s \qquad \textit{if s is unacceptable}$ 3.5

$\sum_t \sum_r \sum_i \sum_a Z_{trisa} \geq \omega_s \qquad \textit{if s is unacceptable}$ 3.6

Non-negativity

$Z_{trisa} \geq 0 \quad \forall\ t, r, i, s, a$ 3.7

where:

Z_{trisa} = Long-term number of lane-miles of pavement category i and traffic category t in region r that are in state s and get treatment a.

Z_{tr} = number of lane-miles of pavement in region r, carrying traffic category t.

AC_{risa} = agency cost in region r of applying treatment a on one lane-mile of pavement category i that is in state s.

UC_{tis} = user (vehicle operating) cost per lane-mile on a pavement of category i and traffic category t that is in state s.

P_{isak} = probability that a pavement of category i will change from state s to state k in one year if treatment a is applied.

δ_s = minimum number of lane-miles in unacceptable state s.

ω_s = maximum proportion of roads in acceptable state s.

3.6 Short-term Repair Policies

The short-term model determines annual repair policies (strategies) over a period of, say, 5-years such that at the end of this period pavement conditions at the network-level will have reached or be near the optimal long-term conditions at which point the long-term policies can be carried out. As is the case in the long-term model, the objective in the short-term model is to minimizes agency and user-cost. The model determines annual repair strategies such that in the last year of this period, short-term policies are as close as possible to the long-term policies.

Equations 3.8 to 3.16 present the short-term model. The results of this model are annual policies ($X_{trisa}^{(y)}$) that specify by volume category t, region r, the number of lane-miles of pavement category i that will be in state s and will get treatment type a in year y.

Short-Term Model

$$\textbf{Minimize} \sum_t \sum_r \sum_i \sum_s \sum_a \sum_y X_{trisa}^{(y)} \left[AC_{risa} + \sum_k UC_{trik} P_{isak} \right] \qquad \text{.....................3.8}$$

Subject to:

Initial year network size by region and traffic category

$$\sum_i \sum_s \sum_a X_{trisa}^{(1)} = X_{tr}^{(1)} \qquad \text{3.9}$$

Annual changes in pavement conditions (Markov process)

$$\sum_a X_{trika}^{(y+1)} = \sum_s \sum_a X_{trisa}^{(y)} P_{isak} \quad \forall\ t, r, i, k \qquad \text{3.10}$$

Consistency of short-term and long-term policies in year T

$$\sum_t \sum_r X_{trisa}^{(T)} \leq Z_{isa}^{*}(1+\zeta) \quad \forall\ i, s, a \qquad \text{3.11}$$

$$\sum_t \sum_r X_{trisa}^{(T)} \geq Z_{isa}^{*}(1-\zeta) \quad \forall\ i, s, a \qquad \text{3.12}$$

Total annual budget

$$\sum_t \sum_r \sum_i \sum_s \sum_a X_{trisa}^{(y)} AC_{risa} \leq B^y(1+\beta) \qquad \text{3.13}$$

$$\sum_t \sum_r \sum_i \sum_s \sum_a X_{trisa}^{(y)} AC_{risa} \geq B^y(1-\beta) \qquad \text{3.14}$$

Total budget constraint over the short-term planning horizon

$$\sum_t \sum_r \sum_i \sum_s \sum_a \sum_y X_{trisa}^{(y)} AC_{risa} \leq B(1+\varepsilon) \qquad \text{3.15}$$

Non-negativity

$$X_{trisa}^{(y)} \geq 0 \qquad \text{3.16}$$

where:

$X_{trisa}^{(y)}$ = number of lane-miles in region *r* which are in pavement category *i*, volume category *t*, and state *s* getting treatment *a* in year *y*.

$X_{tris}^{(y)}$ = number of lane-miles in region *r* which are in pavement category *i*, volume category *t*, and state *s* in year *y*.

Z^*_{isa} = optimal long-term number of lane-miles in the state which are in pavement category i and state s that will get treatment a, (from Long-term model = $Z_{isa} = \sum_r \sum_t Z_{trisa}$).

Z^*_{trisa} = long-term number of lane-miles of pavement category i and traffic category t that are in state s and get treatment a.

AC_{risa} = agency cost in region r of applying treatment a on one lane-mile of pavement category i that is in state s.

UC_{tis} = user (vehicle operating) cost per lane-mile on a pavement of category i and traffic category t that is in state s.

P_{isak} = probability that a pavement category i will change from state s to state k in one year if treatment a is applied.

T = short-term planning horizon.

B^y = annual budget constrain (state level).

B = total budget constrain over the planning period (T years).

b = proportion of annual budget variation.

e = proportion of total budget for the planning period that can be exceeded.

z = proportion of long-term repair policies that can differ from the short-term policies in year T.

The long-term and short-term policies are specified in terms of lane-miles. While these are useful network-level policies, we need to be able to translate these policies into annual project and treatment selection. This process is explained in phase 3 described in Section 3.7.

3.7 ANNUAL PROJECT AND TREATMENT SELECTION

Phase 3 of this network-level analysis determines how the short-term policies can be used to select projects. To do this we need to identify pavement repair projects. The process of project identification is best done by regions instead of being done centrally at the State level. A project is a stretch of highway that the region repairs as a unit. These projects can be as small as the

smallest management units. However, it is desirable that projects are formed, such that repair work on each project can be accomplished in one repair season.

Having identified projects, phase 3 simulates the regional short-term policies and resource constraints on the projects over the planning horizon. The outcome of this simulation are the most probable annual repair actions on these individual projects in the form of, say, a 5-year maintenance and rehabilitation program.

Policy Simulation

The output of phase 2 (see Section 3.6) are short-term annual repair policies $\left(X_{trisa}^{(y)}\right)$ and the annual budget allocations for the region $\left(B_r^{(y)} = \sum_t \sum_i \sum_s \sum_a X_{trisa}^{(y)} AC_{risa}\right)$. In the first year, all projects are listed by lane-miles, average pavement category, average pavement condition, average traffic volume, dominant distress, etc. The projects are then ranked by category, condition, volume and dominant distress. Repair actions are then applied according to the specified policies such that the first-year budget is not exceeded. The most probable conditions of these project for the following year are determined by simulating the Markov process (using the transition probabilities). The process is then repeated for subsequent years for the entire planning horizon. The expenditure recommended by this simulation should closely match the budget since the short-term repair policies are optimal for the given budget levels.

3.7 Short-Term and Long-Term Problem Sizes and Solutions

Both the short-term and the long-term models are formulated as linear programs. Due to the way the decision variables are specified, both of these are large-scale problems.[22] The long-term model that is specified in equations 3.1 - 3.7 has a total of 316,800 decision variables and about 40,000 constraints. The short-term model that is specified in equations 3.8 - 3.16 has a total of 1,584,000 variables and 136,800 constraints. It is almost impossible to try to solve these problems directly, given their sizes. Fortunately, we can take advantage of the structure of these problems and decompose them to smaller solvable problem.

Both problems have constraints that are arranged as shown in Figure A- 3.1. In this figure, the small blocks will be called "easy" constraints, and the last long block will be called "complicating" constraints. In the long-term model, equations 3.2 and 3.3 represent "easy" constraints, (one block for each traffic volume t and region r combination) while equations 3.4 - 3.6 represent "complicating" constraints. Similar to the long-term model, equations 3.9-3.10 represent "easy" constraints, while equations 3.11 - 3.15 are "complicating" in the short-term model.

If we relax the problem by ignoring the "complicating" constraints, then each one of the easy equations becomes an independent problems due to the block angular structure. This means the solution to the long-term model can be obtained by solving 330 ($t*r$ =30*11) independent problems with 960 variables ($i*s*a$ =12*10*8 = 960) and 120 constraints. The solutions to the 330 problems are treated as initial proposals which are improved by taking into consideration the complicating constraints using a decomposition routine until the optimal solution is reached. The short-term model can be solved in a similar way. The easy sub-problems will have 4800 variables and about 600 constraints.

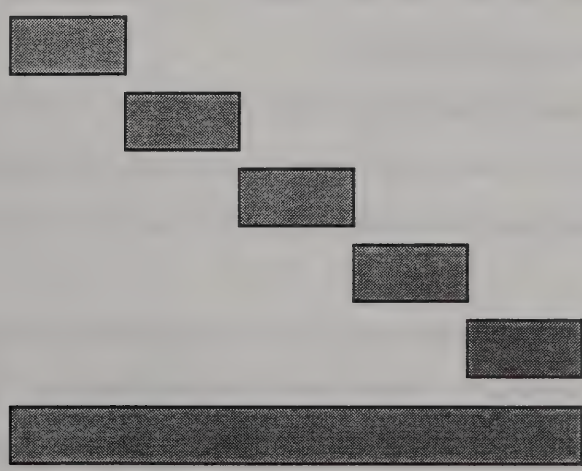

Figure A- 3.1 Structure of long-term and short-term model constraints.

4. PROPOSED PROJECT-LEVEL ANALYSIS PROCEDURES FOR NYSDOT

If the proposed system is to be a "top down" procedure, we need project-level analysis to address the following problem: Given that a project is to be repaired using a particular treatment category - say, rehabilitation, - what is the most cost-effective rehabilitation method to implement? This means project-level analysis will be implementing network-level strategies. Our detailed recommendations for project-level analysis will be presented in a separate forthcoming report.

5. CONCLUSIONS

In this report, we have presented results of a survey of project and treatment selection techniques that are used by agencies in the U. S. and in Canada. The survey results show that currently NYSDOT program analysis procedure (which can be categorized as *a priority assessment method*) is better than the (*pavement condition analysis*) method used by most agencies (47%). These methods are explained in Section 2.1. However, the research team is proposing a top-down program analysis method that will employ optimization techniques. The results of the proposed program analysis procedure are:

- Long-term (steady-state) maintenance and rehabilitation policies (strategies)
- Short-term (5-10 years) maintenance and rehabilitation strategies
- Annual maintenance and rehabilitation program for the short-term.

These optimal policies or strategies will take into consideration the minimization of agency and user costs, and the preservation of agency-specified requirements. The models can either be used to determine optimal budget levels and their subsequent treatment strategies, or they can be used to determine optimal treatment strategies and the consequent network condition, given a budget restriction. The models proposed in this report will be fairly flexible. This means that the Department may, from time to time, decide to change their objective functions or constraints to suit the kind of what-if analysis that may be of interest then. We hope the recommended

procedures address the Department's requirements and that they are in line with the scope of services for this project.

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Glossary of Terms

1. **Action -** *An application of a treatment category to a section of highway pavement.*

2. **Agency Costs -** *The cost of owning a highway system. This includes cost of repairing pavements and roadside items; cost of providing safety, mobility, and capacity; cost of repairing bridges; and overheads.*

3. **Alternatives -** *The various choices of treatments available for repairing a pavement deficiency or problem.*

4. **Analysis Period -** *Time period for which an economic analysis is done.*

5. **Asphalt Cement Concrete -** *A stiff mixture of asphalt cement and aggregates used to make pavements for highways, airfields, play courts, etc.*

6. **Asphalt Cement Concrete Pavement -** *Highway pavements made from asphalt cement concrete.*

7. **Asphalt Cements -** *These a bituminous material (binders) derived from the distillation of petroleum products, lake asphalt or rock asphalt. It is as a binder in the making of asphalt pavements.*

8. **Benefit/Cost (B/C) Analysis -** *An analysis method where economic benefits of a solution are related to the costs incurred in providing the solution.*

9. **Bottom-Up Methods -** *A planning method where the best that can be done to individual projects are considered first before determining what is the best for the entire network given resource limitations.*

10. **Corrective Maintenance -** *Treatment correcting existing deficiency, upgrading the roadway surface for up to 8 years or until more extensive treatments are needed.*

11. **Cost-Effectiveness -** *A situation where the benefits exceed the costs for a given treatment, strategy or improvement, (i.e., B/C-ration > 1).*

12. **Decomposition -** *An optimization routine whereby a large-scale mathematical programming problem is broken down into smaller(solvable) problems whose combined solutions lead to the optimal solution of the larger problem.*

13. **Distress Frequency -** *The rate at which a particular pavement-surface-distress feature (e.g., cracking) occurs.*

14. **Distress Severity -** *The extent to which surface distress feature manifests itself.*

15. **Dominant Distress -** *A specific distress symptom which will trigger a treatment strategy different from the treatment recommended by the surface rating alone.*

16. **Equivalent Standard Axle Load (ESAL) -** *The AASHTO system of equating the damaging effects of a vehicle axle load to that of a standard (18,000 lb. single or 34.000 lb. tandem) axle.*

17. **Flexible Pavements -** *These are pavements made of asphalt cement concrete (full depth asphalt).*

18. **Infrastructure Needs Assessment Model (INAM) -** *A network-level project and treatment selection model used by NYSDOT.*

19. **International Roughness Index (IRI) -** *An index resulting from a mathematical simulation of vehicular response to a longitudinal profile of a traveled surface using the quarter-car simulation model and a travel speed of 50 miles per hour (80 km per hour). Units are in inches per mile or meters per kilometer.*

20. **Life-Cycle Costing -** *An economic assessment of an item, area, system. Or facility and competing design alternatives considering all significant costs of ownership over the economic life, expressed in terms of equivalent monetary units (e.g., dollars).*

21. **Major Rehabilitation -** *Major rehabilitation or pavement reconstruction is a treatment to be considered when the condition of the existing pavement is such that it can no longer serve a useful purpose. When design constraints or life-cycle cost analysis preclude rehabilitation then reconstruction solution is used.*

22. **Markov Decision Process -** *A probabilistic decision support process that assumes that the process driving the system (e.g., pavement performance) can be modeled as a Markov chain (or a random walk).*

23. **Network Optimization Method -** *This is a "top-down" network analysis method whereby network strategies are optimized first followed by individual project solutions.*

24. **Network-Level -** *The level at which key administrative decisions that affect programs for road networks or systems are made. Sometimes referred to as the program level.*

25. **Network-Level Analysis -** *Evaluation of pavement to enable the selection of candidate projects, project scheduling, and budget estimates.*

26. **Optimization Model -** *A mathematical description or algorithm designed to compare alternative strategies and to identify the relative merits of each strategy according to assigned decision criterion, such as cost minimization, benefit maximization, etc.*

27. **Optimum Strategy -** *The strategy among the alternatives considered that is expected to maximize the realization of management goals, subject to the imposed constraints.*

28. **Overlaid Pavements --** *These are rigid pavements overlaid by asphalt cement concrete layer(s).*

29. **Pavement Condition -** *A qualitative representation of distress in pavement at a given point in time.*

30. **Pavement Distress -** *The physical manifestation of defects in a pavement.*

31. **Pavement Maintenance -** *All routine actions, both responsive and preventive, which are taken by a highway agency or other parties to preserve the pavement structure, including joints, drainage, surface, and shoulders, as necessary for its safe and efficient utilization.*

32. **Pavement Management System -***A set of tools or methods that assist decision-makers in finding cost-effective strategies for providing, evaluating and maintaining pavements in a serviceable condition.*

33. **Pavement Performance -** *Ability of a pavement to fulfill its purpose over time.*

34. **Pavement Performance Prediction Model -** *A mathematical description of the expected values that a pavement attribute will take during a specified analysis period.*

35. **Pavement Strength -** *This is a measure of pavement bearing capacity often given by the number of repetitions of ESALs to failure.*

36. **Pavement Structural Capacity -** *The maximum accumulated traffic loads that a pavement can withstand without incurring unacceptable distress*

37. **Pavement Surface Rating Scale -** *The surface rating scale measures surface condition by scores from 10 (excellent) to 1 (very poor) based on the prevalence of surface related pavement distresses (e.g., cracking).*

38. **Performance Prediction Model -***Models that can forecast pavement condition over time.*

39. **Policy Simulations -** *These simulations apply repair policies to pavement sections (or projects) annually, following performance prediction models.*

40. **Portland Cement Concrete -** *A mixture of Portland (normal building construction) cement and aggregates used to make pavements for highways, airfields, play courts, etc.*

41. **Portland Cement Concrete Pavement -** *Highway pavements made from Portland cement concrete.*

42. **Preventive Maintenance -** *Treatment undertaken in advance of a critical need or of accumulated deterioration to avoid such occurrences and reduce or arrest the rate of deterioration, thus allowing roadway surfaces to achieve their desired service life.*

43. **Project -** *A pavement section designated to receive a uniform treatment category.*

44. **Project-Level -** *The level at which technical management decisions are made for specific projects or pavement segments.*

45. **Project-Level Analysis -** *Evaluation of pavement to select the type and the timing of rehabilitation or maintenance.*

46. **Quarter-Car Simulation -** *A method of analyzing pavement profile data based on the one wheel-assembly (hence, quarter-car) model. The parameters of a quarter-car include the sprung mass of a vehicle body; the suspension spring and damper (shock absorber) constants; the unsprung mass of the suspension, tire, and wheel; and the spring constant of the tire.*

47. **Reconstruction -** *Construction of the equivalent of a new pavement structure which usually involves complete removal and placement of the existing pavement structure including new and/or recycled materials.*

48. **Rehabilitation -** *Resurfacing, restoration, and rehabilitation work undertaken to restore serviceability and to extend the service life of an existing facility. This may include partial recycling of the existing pavement, placement of an additional surface material or other work necessary to return an existing pavement, including shoulders, to a condition of structural of functional adequacy.*

49. **Repair -** *Includes all treatment categories.*

50. **Repair Policies -** *These a strategies that will specify an optimal treatment category, given pavement condition, type, strength, traffic volume, etc.*

51. **Rigid Pavements -** *These are pavements made of Portland cement concrete.*

52. **Rubblize -** *A process of breaking down rigid pavements into a rubble and compacting it to form a base ready for asphalt concrete overlay.*

53. **Strategy -** *A plan or method for dealing with all aspects of a particular problem. For example, a rehabilitation strategy is a plan for maintaining a pavement in a serviceable condition for a specified time period or it could be a set of maintenance rehabilitation or reconstruction actions selected to preserve the entire network at specified levels of performance.*

54. **Sustainable Management Policies -** *These are pavement repair strategies that, if followed, will sustain the network at the specified condition and budget.*

55. **The Department -***This term refers to the New York State Department of Transportation.*

56. **Top-Down Method -** *A planning method where the best that can be done for the entire system is considered first, which in turn determines what needs to be done to individual projects, given resource limitations.*

57. **Transition Probability -** *The probability of a pavement section to change from its current condition to another condition in one year.*

58. **Treatment Categories -** *General categorization of pavement treatments. These include do-nothing, preventive maintenance, corrective maintenance, rehabilitation, and major rehabilitation. Each treatment category comprises different alternative treatments depending on pavement type, surface condition rating, dominant distress, and traffic volume.*

59. **Treatments -** *Materials and methods used to correct a deficiency in a pavement surface.*

60. **User Costs -** *Those costs that are accumulated by the user of a facility. In a life-cycle cost analysis these could be in the form of delay costs or change in vehicle operating costs.*

Acronyms

AASHTO	*American Association of State and Transportation Officials*
ACC	*Asphalt Cement Concrete*
ACCP	*Asphalt Cement Concrete Pavement*
CERL	*Construction Engineering Research Laboratory (United States Army)*
CUNY	*City University of New York*
ESAL	*Equivalent Standard Axle Load*
FHWA	*Federal Highway Administration*
GOCP	*Goal-Oriented Capital Program*
HCPM	*Highway Condition Project Model*
INAM	*Infrastructure Needs Assessment Model*
IRI	*International Roughness Index*
LCC	*Life-Cycle Cost*
MDP	*Markov Decision Process*
NCHRP	*National Cooperative Highway Research Program*
NYSDOT	*New York State Department of Transportation*
PCC	*Portland Cement Concrete*
PCCP	*Portland Cement Concrete Pavement*
PMS	*Pavement Management System*
vpd	*Vehicles per day*

PART B

B. Evaluation and Recommendations on NYSDOT Pavement Life Predictive Models

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1. Introduction

1.1 Role of Pavement Performance Prediction in Pavement Management

The role of pavement management and pavement management systems (PMSs) has been defined in the literature, and was repeated in Part A of this Report. However, as Baladi and Fult[1] point out, "…none of these definitions … address … main purpose of a PMS, which is to provide its users with opportunities to learn from their successes and failures." The PMS process is a continuing education process whereby users continue to calibrate and sharpen their tools to improve efficiency and productivity. In this context, PMS issues, such as implementation, data collection, pavement performance models, and decisions become learning issues.

A major PMS learning tool is the frequent evaluation of pavement conditions. The evaluation of a pavement section may involve the appraisal of its functional, safety, and structural conditions. Historical pavement condition data typically are used to assess pavement performance over time. However, the term "pavement performance" usually is defined as how well a pavement section serves the user over time. This definition has led some engineers and highway agencies to use pavement ride quality as the only or as the major attribute of pavement performance. Other engineers and highway agencies believe that pavement performance should include pavement distress, structural capacity, and safety.

The performance of a pavement section over time can be divided into three levels: functional, structural, and safety. For example, the ride quality (functional performance) of a smooth but polished aggregate road can be superior, whereas its safety performance is poor. Likewise, a newly constructed pavement can have a poor ride quality (high roughness), whereas its structural capacity is very sound. In general, the structural distress (structural capacity) of pavement section also will affect its functional and safety performance. But a functional or safety distress may not affect the structural capacity of a pavement. Hence, pavement performance models that are based mainly on ride quality may have limited application.'

On another scale, the type of pavement performance data collected and the extent (level of detail) to which the data are collected depend on the decision level of the PMS. Project-level PMS requires detailed structural, functional, and safety data to be able to make the necessary designs

and recommend appropriate construction strategies. However, in a network-level PMS less detailed data of pavement structural performance (e.g., index of surface distress) and functional performance can be used to come up with broad network strategies and resource requirements that are appropriate at this level of pavement management. Therefore, pavement performance models will differ, depending on the level of PMS for which they are intended. In this report we will be interested in pavement performance and pavement performance predictions for a network-level PMS.

1.2 Summary of the Contents of this Report

Section 2 of this report reviews current measures of pavement performance and performance predictive models used by NYSDOT and other agencies in the US and Canada. In view of the decision support model proposed in Part A of this Report, we recommend probabilistic pavement performance models for the NYSDOT network-level PMS. Section 3 presents a general overview of probabilistic (Markov/Semi-Markov) pavement performance models and their estimation process. Section 4 estimates these models using historical data from the entire State. This section also discusses some of the precautions that need to be taken in order for these models to be even more effective in the decision support system proposed in Part A.

2. Pavement Performance Modeling

2.1 General

The prediction of pavement performance over time is essential to a dynamic decision support system. However, there are many pavement indicators that can be used to measure performance. These measures include:

- Distress (e.g., cracking, rutting, spalling, etc.)
- Roughness (riding comfort rating)
- Structural Capacity
- Surface Friction

2.2 Survey of Pavement Performance Data and Data Collection Methods

As mentioned earlier in this report, pavement performance data can be collected at different levels. These levels are structural performance data (either in the form of surface distress, which can be used as an indicator of structural capacity, or as direct and detailed structural capacity data), functional performance (e.g., ride quality or surface roughness data), and safety performance data (mainly in the form of friction data).

In 1994, National Cooperative Highway Research Program Synthesis 203 (NCHRP Synthesis 203)[2] reported results of a survey of "Current Practices in Determining Pavement Condition" that was conducted for 60 highway agencies in the US and Canada. This report summarizes different methods used by these agencies for measuring pavement distress, roughness, structural, and friction (or safety) conditions. It is reported that nearly all agencies surveyed collect some form of pavement roughness and distress data. Most agencies also conduct pavement friction testing. However, about a third of these agencies do not consider pavement friction data collection as part of their PMS function. About 38% of the agencies surveyed perform detailed structural evaluations, but these are mainly used for specific project-level designs rather than for network-level evaluation. The following sections further define what variables are evaluated in these various performance measures. Four performance measures will be discussed, namely: *Distress, Roughness, Structural Capacity, and Friction.*

Distress

Pavement distress is a measure of surface and subsurface deterioration (mainly structural deterioration) as a consequence of traffic loading, time, and climatic factors. Currently, there are no nationally accepted standards for either the procedures or the equipment to be used in collecting distress information.[2] However, efforts are underway either to standardize or harmonize this process. According to NCHPR Synthesis 203[2], distress data are usually collected by type, extent, and severity. Distress types tend to fall into three general categories regardless of roadway surface type: cracking, surface deterioration, and distortion. However, the way in which the specific distress types, severities, and extents are defined vary by the geographic location and the types of distress generally prevalent in an agency's pavements.

Four methods of collecting distress data were reported in the NCHRP report.[2] These are *windshield, shoulder, walking, combination* and *automated.* Windshield method is by far the most commonly used method of distress data collection. In a windshield method the surveyor sits in a car traveling on the surveyed section and collects distress data while viewing the pavement through the windshield. A shoulder method is similar to the windshield method except that the survey car travels on the shoulder and the surveyor collects distress data by viewing the travel-lane pavement. Walking surveys are conducted on foot where the surveyor walks on the pavement while collecting distress data. There are agencies that use a combination of these three methods while a few use automated systems to collect distress data. As an output of these distress surveys, the majority of agencies summarize their data in some form of an index per highway section. These indices can be purely distress related or a combination of distress and other types of pavement performance like roughness, structural capacity or friction. Appendix B presents a summary of current practices of collecting distress data as reported by NCHRP Synthesis 203.[2]

Roughness

Road roughness is a measure of pavement ride quality. In addition to its ability to measure road users' ride comfort, road roughness also has a direct relationship to vehicle operating cost (e.g., fuel consumption, tire wear and tear, vehicle maintenance cost, etc.). Whereas pavement *distress* and *structural capacity* data are used to determine appropriate repair actions and hence, the extent of agency cost, roughness data is useful in rating pavement functional performance and can, therefore, be used to assess user cost (comfort, vehicle operating/owning cost, etc.). There are many methods of measuring road roughness. These methods can be categorized into four classes. Class I devices involve high precision road profile measurements. These precision profiles are recorded along the longitudinal wheelpath and are said to provide the highest level of precision and repeatability.[2] Class II devices still measure longitudinal profiles but at lower accuracy and have to be frequently calibrated using class I devices. Class III devices have even lower levels of accuracy and have to be calibrated on sections whose profiles were measured by either class II or class I devices. Class IV type of roughness measurement involves subjective assessment of riding comfort either by riding on the pavement section or doing visual inspection.

However, regardless of the device used, roughness is one of the pavement performance measures that is close to being standardized all over the world. This standard roughness measure is the International Roughness Index (IRI). IRI is a standardized roughness measure (based on the World Bank data[3]) and data from many methods of measuring longitudinal profiles can be correlated with their equivalent IRI. The majority of agencies in the NCHRP[2] survey report their roughness data in terms of IRI. Appendix C presents a summary of current practices of collecting roughness data, as reported by NCHRP Synthesis 203.[2]

Structural Capacity

Pavement structural capacity is a measure of its ability to bear traffic loads with minimum fatigue distress or deformation. The evaluation of this capacity is needed to assess pavement's current ability to carry loads and its remaining life. However, this evaluation is often so detailed and costly that it is usually reserved for the specific sections where detailed information is needed for the final designs and selection of rehabilitation alternatives. Structural evaluation requires some form of physical measurements on the pavement. These measurements can be destructive (e.g., coring pavement samples) or non-destructive where pavement response (e.g., deflection) due to known load is measured. Some of the non-destructive testing equipment reported in NCHRP Synthesis 203[2] include Benkelman beam, Dynatest, Dynaflect, Falling Weight Deflectometer (FWD), etc. Appendix D presents a summary of current practices of collecting distress data as reported by NCHRP Synthesis 203.[2]

Friction

Pavement friction is a measure of skid resistance of tires on wet pavement. If data on pavement friction is incorporated into a PMS, aspects of highway safety can be checked. Most of the agencies in the NCHRP Synthesis 203[2] have a friction testing program. Appendix E presents a summary of current practices of collecting friction data as reported by NCHRP Synthesis 203.[2]

2.3 PERFORMANCE OF NYSDOT PAVEMENT.

As indicated in NCHRP Synthesis 203[2], NYSDOT collects data on pavement distress, roughness, and friction. Distress data is collected annually, using the windshield method on 100 percent of NYSDOT highway sections. The results of this exercise are raw scores of distress ranging from 1 to 10, 10 being the best (as new) surface condition. These raw section scores are further used to get average regional distress ratings. Distress surveys are normally conducted by NYSDOT personnel using photographic scales. These photo scales were developed in 1981 as reported by Hartgen et al.[4] The data is recorded on preprinted data sheets and is later transferred to computers for storage and processing. NYSDOT uses the results of these distress scores to specify treatment strategies on its highways. Figure B- 2.1 below shows the categorization of pavement performance based on the distress scale, and it also shows what treatment strategies are recommended for the different levels of distresses.

NYSDOT also collects roughness data. However, this is done on only a sample (about 1000 miles). The survey is normally contracted out and is done biannually. Roughness data is reported in terms of IRI units. Another pavement performance characteristics collected by NYSDOT is friction. This is done using ASTM trailer and the data is collected three times a year. The friction data is reported per test, as well as per mile. The data is then stored in the mainframe computer for analysis.

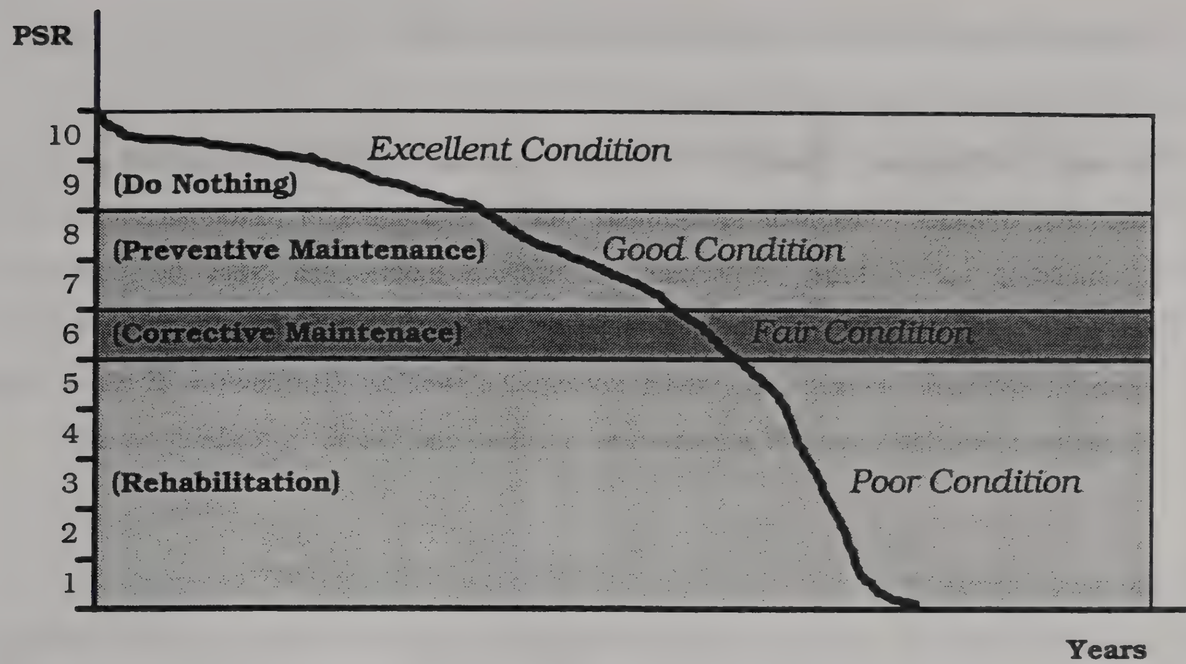

Figure B- 2.1. NYSDOT Distress Scale and Treatment Strategies.

Performance Models

In order to specify pavement repair strategies over time, an agency needs to be able to predict pavement performance. This is done by fitting a deterioration curve using historical performance data. NYSDOT has these performance models, based on the distress data, for all its highways. These models are fitted using regression models and are of the form:

$$\textit{Distress}\ (\textit{in}\ \text{year y}) = 10 - \alpha \sqrt{y}$$

where: α = a constant (specific to the type of pavement, e.g., rigid, overlaid or flexible))

The choice of a performance model very much depends on the PMS analysis tools employed. Regression models predict average (expected) performance of pavements. These models are suited to deterministic decision support systems. On the other hand, if stochastic decision support systems are used (as is the case with the proposed PMS models - see Task-1 Report[5]), then stochastic performance models are more appropriate.

3. Stochastic Modeling of Pavement Performance

3.1 Pavement Performance Models

Pavement Management Systems (PMSs) require accurate and efficient pavement performance prediction models. Pavement performance describes changes in pavement condition due to accumulating use or time. Pavement performance models can either be deterministic or stochastic. Deterministic models predict average values of pavement performance measures. In contrast, stochastic models can predict averages as well as distributions of these measures. Examples of stochastic models include survival curves and Markov probability models.

Survival Curves

Survival curves fall under the category of stochastic models. A survival curve is a graph of probability versus time. It shows the proportion of pavements that remain serviceable after a number of years. Given survival curves and network goals, an agency can determine network maintenance strategies.

Markov Probability Models

The most versatile stochastic performance models that can be used in network-level PMSs are models based on the Markov process. A lot of work in PMSs is directed to systems based on the Markov decision process. The rest of this chapter focuses on these models.

3.2 Markov Performance Models

Markov performance models express pavement performance in the form of a Markov transition probability matrix. These transition probabilities give the likelihood that pavements with similar characteristics will change from one condition-state to another in a given period. The following assumptions are made when modeling pavement performance as pure Markovian:

1 There are a finite number of condition-states in which a pavement can be. These condition-states can be intervals of the distress scale.

2 The probability that a pavement will transition from one state to another depends only on the present state and action. This assumption is easy to accommodate if pavements are categorized into performance-homogeneous groups. We will discuss this point later.

3 The transition process is stationary. This means that the transition probabilities do not change with time. This condition can be changed so that the transition probabilities change over time. The resulting probabilities and decision support tools are often referred to as semi-Markov.

Condition-States

Before discussing the estimation of transition probabilities we need to define the different condition-states a road pavement can be in and the factors that may cause changes in these condition-states. As outlined above, NYSDOT uses Pavement Surface Ratings or scores to define pavement distress condition-states. Figure B- 2.1 shows that scores of 9 and 10 signify an excellent surface conditions, 7 and 8 refer to good surface conditions, 6 is fair, while 5 to 1 refer to poor surface conditions. In modeling pavement distress using Markov transition probabilities, we will define condition-states as being equal to surface scores.

Transition Probabilities

Markov pavement performance modeling is achieved by estimating the transition probabilities. We need an efficient method of estimating and updating these transition probabilities. When probabilities do not vary with pavement age, they are referred to as stationary or homogeneous, otherwise they are non-homogeneous. Non-homogeneous transition (semi-Markov process) implies that, given the same initial condition-state, two pavements having the same pavement type but different ages will deteriorate differently. Butt et al.[6] have shown some evidence of this phenomenon for flexible (asphalt) pavements, but the difference in deterioration rates was very small. Due to the convenience of using homogeneous transition probabilities in both performance and maintenance investment modeling, we will assume homogeneity in the transition probabilities, knowing very well that this may introduce a slight bias in performance prediction. Therefore, the transition probabilities will be associated with the pavement

condition-states defined above. The following definitions and assumptions about transition probabilities are made:

(1) p_i is the probability that a pavement in condition-state i will remain in that condition-state after one duty-cycle (a year of weather exposure and traffic loading).

(2) q_i is the probability that a pavement in condition-state i will deteriorate to the next lower condition-state after one year.

(3) r_i is the probability that a pavement in condition-state i will deteriorate by two levels of condition-states after one year.

(4) Pavement condition will not drop by more than two condition-state (i.e., 2 score points) during one year. From observed historical distress data[7,8] this assumption seems plausible.

(5) Pavement condition-states cannot go up as a result of routine or preventive maintenance. An upward change in state can only take place if a corrective maintenance (e.g., chip seal), major rehabilitation, or reconstruction work is performed.

(6) Condition-state 1 is a holding (or trapping, or absorbing) condition-state. Once a pavement is in this condition-state it cannot get out unless major repair (rehabilitation or reconstruction) work is done to it.

These transition probabilities can be conveniently represented in a matrix form - ***P***, as shown in Figure B- 3.1 below.

3.3 TRANSITION PROBABILITY ESTIMATION MODEL

Pavement condition-state, at any period n, can be represented by a state-vector $S^{j}_{(n)}$. This is a vector of probabilities that specify the likelihood of a pavement to be in various condition-states at period n, having started in condition-state j. In the initial period (year), we are sure that the road is in a particular condition-state, say condition-state 10. So the state-vector will look like $S^{(10)}_{(0)} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$. Therefore, for a pavement that started in condition-state j, the state-vectors at any other period are given by:

$$S_{(1)}^{(j)} = S_{(0)}^{(j)}P$$

$$S_{(2)}^{(j)} = S_{(1)}^{(j)}P = S_{(0)}^{(j)}P^2$$

$$S_{(3)}^{(j)} = S_{(2)}^{(j)}P = S_{(1)}^{(j)}P^2 = S_{(0)}^{(j)}P^3 \qquad \text{.....................................3.1}$$

$$\cdot$$

$$S_{(n)}^{(j)} = S_{(n-1)}^{(j)}P = \text{..........} = S_{(n)}^{(j)}P^n$$

where P is the matrix of transition probabilities shown in Figure B- 3.1.

$$\begin{bmatrix} p_{10} & q_{10} & r_{10} & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & p_9 & q_9 & r_9 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & p_8 & q_8 & r_8 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & p_7 & q_7 & r_7 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & p_6 & q_6 & r_6 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & p_5 & q_5 & r_5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & p_4 & q_4 & r_4 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & p_3 & q_3 & r_3 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & p_2 & q_2 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

Figure B- 3.1: Matrix of Transition Probabilities

A set of all possible state-vectors in the initial year is an identity matrix, i.e.,

$$S_0 = \begin{vmatrix} S_{(0)}^{(10)} \\ S_{(0)}^{(9)} \\ S_{(0)}^{(8)} \\ S_{(0)}^{(7)} \\ S_{(0)}^{(6)} \\ S_{(0)}^{(5)} \\ S_{(0)}^{(4)} \\ S_{(0)}^{(3)} \\ S_{(0)}^{(2)} \\ S_{(0)}^{(1)} \end{vmatrix} = \begin{vmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 \end{vmatrix} = I$$

The set of all possible state-vectors for any other year is given by the following matrices, based on the Chapman-Kolmogorov equations.

$$S_{(1)} = S_{(0)} P = P$$

$$S_{(2)} = S_{(1)} P = S_{(0)} P^2 = P^2$$

$$S_{(3)} = S_{(2)} P = S_{(1)} P^2 = S_{(0)} P^3 = P^3 \qquad \text{.................................... 3.2}$$

$$\cdot$$

$$\cdot$$

$$S_{(n)} = S_{(n-1)} P = \text{..........} = S_{(0)} P^n = P^n$$

Therefore, the state-vector in period n for a pavement that started in condition-state j, is the jth row vector of the matrix P^n. The vector of expected pavement conditions (in PSR) at any period n is given by:

$$E_n = C\left(P^n\right)^{Transpose} \qquad \text{...3.3}$$

where, $C = (10, 9, 8, 7, 6, 5, 4, 3, 2, 1)$.

E_n is a row vector whose kth element (E_n^k) is the expected condition in period n for a pavement that started in condition-state or PSR (11-k). The following expressions show some examples of E_n^k in terms of p and q.

Probability Estimation Model

In order to estimate transition probabilities from historical data, our objective will be to find those values of $p \in \Re^{17}$ (17th dimension Euclidean space) that will minimize the sum of squared differences between the observed PSR and the corresponding expected PSR as estimated by equation 3.3. A nonlinear programming model (Equation 3.4) using a Davidon-Fletcher-Powell algorithm[9,10,11] is used to estimate these probabilities.

Nonlinear Program 3.4

$$\textit{Minimize} \sum_{i=1}^{N}\sum_{j=1}^{Y_i}(PSR_{sj}^{i} - \overline{PSR}_{sj}^{i})^2$$

$$\textit{Subject to} \qquad p_s,\ q_s,\ r_s \leq 1$$

$$p_s,\ q_s,\ r_s \geq 0$$

where,

N = total number of pavement sections, of a particular pavement category, whose historical data on their condition-states are available.

Y_i = total number of consecutive years (periods) for which condition data is available for pavement section i (not counting the first data point).

PSR_{sj}^{i} = observed condition-state of pavement section i, in period j that started in condition-state s.

$\overline{PSR}_{sj}^{i}$ = expected condition-state in period j for pavement section i that started in condition-state s (derived from equation 3.3).

p_s, q_s, r_s = transition probabilities corresponding to condition-state s.

4. Estimation of Distress Performance Models for NYSDOT Pavements

4.1 General

This section presents the results of pavement performance models which were developed based on the Markov transition probabilities discussed in Section 3. These models are in the form of transition probabilities as well as average performance curves. All transition probability matrices can be found in Appendices F-1 to F-3. These probabilities will be used in the network-level PMS, a decision support system described in the Task-1 Report.[5] In order to facilitate model comparisons, the average performance curves (based on these transition probabilities) are used in this section. The average performance curves are suited for comparing performance models among categories. For instance, these curves can be used to show regional variation in pavement performance, effect of traffic loading on performance, etc.

Before these models can be estimated, it is important to group pavements into categories which are likely to be performance-homogeneous. This categorization process is important in two ways. First, it will lead to performance models for pavements of similar characteristics, hence it ismore reliable. Secondly, these performance-homogeneous categories are a prerequisite to the use of Markov transition probabilities as models for pavement performance. One of the assumptions of a Markov process is that the condition of a pavement section in the next period depends only on its present condition and not on its historical trend. This assumption will only hold for highway pavements if they are grouped into categories that have similar historical trends and similar deterioration propensities. If this categorization is done then, within each category, the performance of a pavement section can be modeled as a Markov process.

To start with, a summary of the NYSDOT highway system is presented in Section 4.2. Section 4.3 presents the method used in grouping highway pavements into performance-homogeneous categories. Section 4.4 discusses the relevance and effects of each factor used to categorize pavements. In this section average performance curves are used for this comparison. Section 4.5 summarizes the results of the performance models estimation process. Transition probability matrices for all pavement categories are presented in Appendices F-1 to F-3.

4.2 SUMMARY OF NYSDOT HIGHWAY NETWORK

The state highway system under NYSDOT has about 15,000 centerline miles or about 37,000 lane-miles of highway. Table B- 4.1 shows the distribution of distress condition of state highway system between 1988 and 1994. This table shows that the average condition (based on the pavement surface distress score) of the state highway system has remained steady between 6.7 and 6.9.

TABLE B-4.1 PAVEMENT PERFORMANCE OF THE NEW YORK TOURING ROUTE SYSTEM (1988-1994)

Source: NYSDOT Highway Sufficiency Ratings

The table also shows that in the period between 1988 and 1994, the majority of the pavements (over 70%) were rated 6 to 8 (i.e., fair to good condition). Table B- 4.2 summarizes this trend of pavement distress condition by each of the 11 regions in the state.

TABLE B-4.2 STATE HIGHWAY SYSTEM REGIONAL TRENDS 1988-1994

Average Condition Ratings							
Region	**1988**	**1989**	**1990**	**1991**	**1992**	**1993**	**1994**
1	6.91	6.88	6.72	6.98	7.02	7.05	7.00
2	6.67	6.56	6.30	6.50	6.58	6.76	6.93
3	6.89	7.07	6.74	6.66	6.46	6.53	6.50
4	6.79	6.85	6.67	6.82	6.86	6.82	6.65
5	6.90	7.02	6.93	6.95	6.96	6.94	6.90
6	6.70	6.54	6.47	6.65	6.65	6.80	6.68
7	6.62	6.34	6.46	6.36	6.54	6.53	6.51
8	7.03	7.09	7.06	7.15	7.07	6.84	6.69
9	7.23	6.97	6.87	6.90	6.82	6.54	6.63
10	7.01	6.99	6.93	7.04	7.05	7.06	7.09
11	6.73	6.21	6.15	6.11	6.13	6.07	5.92
Total	**6.89**	**6.84**	**6.73**	**6.81**	**6.81**	**6.78**	**6.74**

TABLE B-4.3 STATE HIGHWAY SYSTEM BY PAVEMENT TYPE

State Highway System 1994 Surface Scores by Pavement Type				
	RIGID	OVERLAID	FLEXIBLE	TOTAL
Lane-miles	4821.34	19300.33	12413.57	36535.24
% of Total	13.2	52.8	34	100
Average Condition	6.37	6.75	6.85	6.74
% Poor	22.6	13.1	11.5	13.8
% Fair	35.4	33.8	30.3	32.8
% Good	40.2	44.4	47.5	44.9
% Excellent	1.9	8.7	10.7	8.5

There are three main types of pavements under NYSDOT care. These are RIGID pavements, OVERLAID pavements, and FLEXIBLE pavements. In 1994, the majority of the state highway system (53 %) consisted of overlaid pavements, followed by flexible pavements (34%), and rigid pavements (13%). Table B-4.3 summarizes the 1994 pavement composition of the state highway

system. This table also shows the distribution of pavement distress among the different pavement types.

4.3 Pavement Categorization

The performance of highway pavements depends on a number of factors. These factors include:

- Pavement Type (e.g., rigid, overlaid or flexible)
- Pavement Strength (or pavement's structural capacity)
- Traffic Loading (mainly by trucks)
- Environmental or Regional Conditions (includes all variant regional factors)
- Treatment Type (a measure of pavement's added structural capacity)

All pavements were grouped into categories based on the above factors. This process is expected to generate groups of pavements that are performance-homogeneous. As mentioned in Section 4.2, this categorization is necessary to justify using Markov transition probabilities to model pavement performance.

4.3.1 Regional Variation

There are many reasons why pavement performance models should be developed by region. First of all, there are climatic variation among regions which may have varying effects on pavement surface conditions. For example, regions that get a lot of ground frost may experience accelerated pavement deterioration during spring thaw compared to regions that do not have such conditions. Other reasons that may lead to regional variations in pavement performance include quality of pavement construction and repair work, construction materials used, traffic composition, etc. The advantages of estimating pavement performance models by region is that the resulting maintenance and rehabilitation policies generated by the PMS decision support model (see Task-1 Report[5]) will be sensitive to regional variations in pavement quality and rates of deterioration.

NYSDOT has 11 regions as shown in Figure B- 4.1. These regions were grouped into five zones:

Zone A	Regions 1 and 2
Zone B	Regions 3, 4 and 5
Zone C	Regions 6, 8 and 9
Zone D	Region 7
Zone E	Regions 10 and 11

For each one of these five zones pavements were further categorized in terms of the other four factors discussed in Sections 4.3.2 to 4.3.5, and then models were estimated for each category.

4.3.2 Pavement Type

Pavements were grouped according to their types. Three types, namely: Rigid Pavements (pavements whose surface layer is made up of Portland cement concrete), Overlaid Pavements (which are old rigid pavements overlaid with asphalt concrete layer), and Flexible Pavements (pavements whose surface and/or base layers are made-up of asphalt concrete). This categorization is important because of the different materials used in the construction of these pavements. Furthermore, failure modes and distress characteristics and rates differ among these three types of pavements.

Figure B-4.1: Map of New York State Showing Counties and the 11 NYSDOT Regions

4.3.3 Pavement Strength

Pavement performance depends on the strength of its constituent layers. One would expect a weak pavement to deteriorate faster that a strong pavement, given equal traffic loading. The criterion used to come up with these strength groups is the type and thickness of the layers making up a pavement, such as surface layer, base layer, or sub-base layer. Table B- 4.4 shows codes used by NYSDOT to categorize types of pavement layers.

TABLE B- 4.4 PAVEMENT LAYER CATEGORIZATION USED BY NYSDOT

SURFACE TYPE		BASE TYPE		SUB-BASE TYPE	
Code	Materials Used	Code	Materials Used	Code	Materials Used
0	Surface and base one and the same	0	Base and sub-base one and the same	0	Natural soil, not graded or drained
1	Bituminous surface treatment	1	Natural soil, stabilized	1	Natural soil, improved
2	Bituminous macadam (mixed in place)	2	Gravel, stone, slag, etc.	2	Natural soil, graded & drained with improved alignment
3	Bituminous macadam (penetration)	3	Gravel, stone, slag, etc. (stabilized by other than bitumunous binders)	3	Selected soils (not gravel or rock) 12" or less
4	Asphalt concrete or plant mix	4	Gravel, stone, slag, etc. (with bituminous binder, 6" or less)	4	Selected soils (not gravel or rock) over 12"
5	Waterbound macadam	5	Gravel, stone, slag, etc. (with bituminous binder, over 6")	5	Gravel, stone, etc. (12" or less)
6	Portland cement concrete (8" or less)	6	Portland cement concrete (8" or less)	6	Gravel, stone, etc. (over12")
7	Portland cement concrete (over 8")	7	Portland cement concrete (over 8")	7	Other (bridges, culverts, etc.)
8	Brick or block	8	Brick or block		
9	Unreinforced concrete	9	Dual type, rigid		

NYSDOT classifies pavements using three digits. These digits correspond to layer codes shown in Table B- 4.4. The first digit is for surface type, the second digit is for base type and the third digit is for sub-base type. For example, a pavement with code 451 is a flexible pavement with a plant mix surface-layer, a bituminous stabilized gravel or stone base-layer over 6" thick, and an improved natural soil sub-base. Based on these layer types, pavements were categorized as either weak or strong. Table B- 4.5 shows layer codes for the weak and strong categories in each pavement type.

TABLE B- 4.5 PAVEMENT STRENGTH CATEGORIES FOR NYSDOT HIGHWAY SYSTEM

	Pavement Categories					
	Flexible		Overlaid		Rigid	
	Weak	Strong	Weak	Strong	Weak	Strong
LAYER CODES	122, 132 135, 142 145, 152 155, 222 232, 235 242, 245 321, 322 332, 335 342, 343 344, 345 346, 402 403, 405 406, 411 421, 422 425, 431 432, 433 434, 435 441	107, 157 207, 355 407, 427 437 442-447 450-457 505	162-167 460-464 480-484	177 465-477 490-497	062, 065 602, 632	072, 075 702-755

4.3.4 Traffic Loading

Pavements were further categorized based on levels of traffic loading imposed on them. Pavement distress is an indication of deteriorating structural capacity. Truck traffic contributes the bulk of structural damage to pavements, hence it will be used to group pavements into two loading groups, namely HIGH (truck traffic greater than or equal to 1,000 vehicles per lane per

day), and LOW (truck traffic less than 1,000 vehicles per lane per day). These volumes of truck traffic were chosen because it was evident from the distress data that the rates of deterioration were different for pavement sections having truck traffic below and above these volumes.

4.3.5 Treatment Type

In order to capture the effect of treatment type on pavement performance it was decided to take this factor into consideration in estimating performance models. For example, if a pavement section deteriorates to, say, surface score 4 and is then rehabilitated, its subsequent deterioration rate will depend on the type of rehabilitation treatment (e.g., 3" overlay, or 6" overlay, or reconstruction) applied, even though its surface score went up to 10 soon after the treatment. Therefore, the performance models estimated in this report will be specific to the preceding treatment.

Four categories of treatments were used for flexible and overlaid pavements. These categories correspond NYSDOT work types as follows:

Treatment Category 1:	Single course asphalt concrete overlay	1" - 1.5"
Treatment Category 2:	Two course asphalt concrete overlay	2.5" - 3"
Treatment Category 3:	Three course asphalt concrete overlay In-place recycling, surface course only	4" - 6" or
Treatment Category 4:	In-place recycling, full depth or Reconstruction or New pavement.	

Only one treatment category was used for rigid pavements, namely reconstruction or new pavement.

4.4 Pavement Distress Model Results

After grouping pavement sections into performance-homogeneous categories as explained above, performance models, in the form of Markov transition probabilities, were estimated using the non-linear programming formulation shown in Equation 2.4. An example of these transition

probabilities is shown in Table B- 4.6. Transition probabilities for all pavement categories are in Appendices F-1 to F-3. Equation 2.3 was used to translate these transition probabilities into average performance curves. Figure B- 4.2 shows an example of an average performance curve for a pavement category whose transition probabilities are shown in Table B- 4.6.

TABLE B- 4.6 ONE-STAGE MARKOV TRANSITION PROBABILITY MATRIX FOR A FLEXIBLE PAVEMENT:

(2.5-3" Overlay on a Low Trafficked, Strong Pavement in Regions 6,8,9)

$$\begin{bmatrix}
\mathbf{0.1421} & \mathbf{0.6130} & \mathbf{0.2448} & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\
0.0000 & \mathbf{0.5612} & \mathbf{0.3825} & \mathbf{0.0563} & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & \mathbf{0.6695} & \mathbf{0.2886} & \mathbf{0.0418} & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & 0.0000 & \mathbf{0.7556} & \mathbf{0.1770} & \mathbf{0.0673} & 0.0000 & 0.0000 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & \mathbf{0.9146} & \mathbf{0.0416} & \mathbf{0.0437} & 0.0000 & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & \mathbf{0.9474} & \mathbf{0.0332} & \mathbf{0.0194} & 0.0000 & 0.0000 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & \mathbf{0.9500} & \mathbf{0.0288} & \mathbf{0.0212} & 0.0000 \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & \mathbf{0.9500} & \mathbf{0.0261} & \mathbf{0.0239} \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & \mathbf{0.5000} & \mathbf{0.5000} \\
0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & 0.0000 & \mathbf{1.0000}
\end{bmatrix}$$

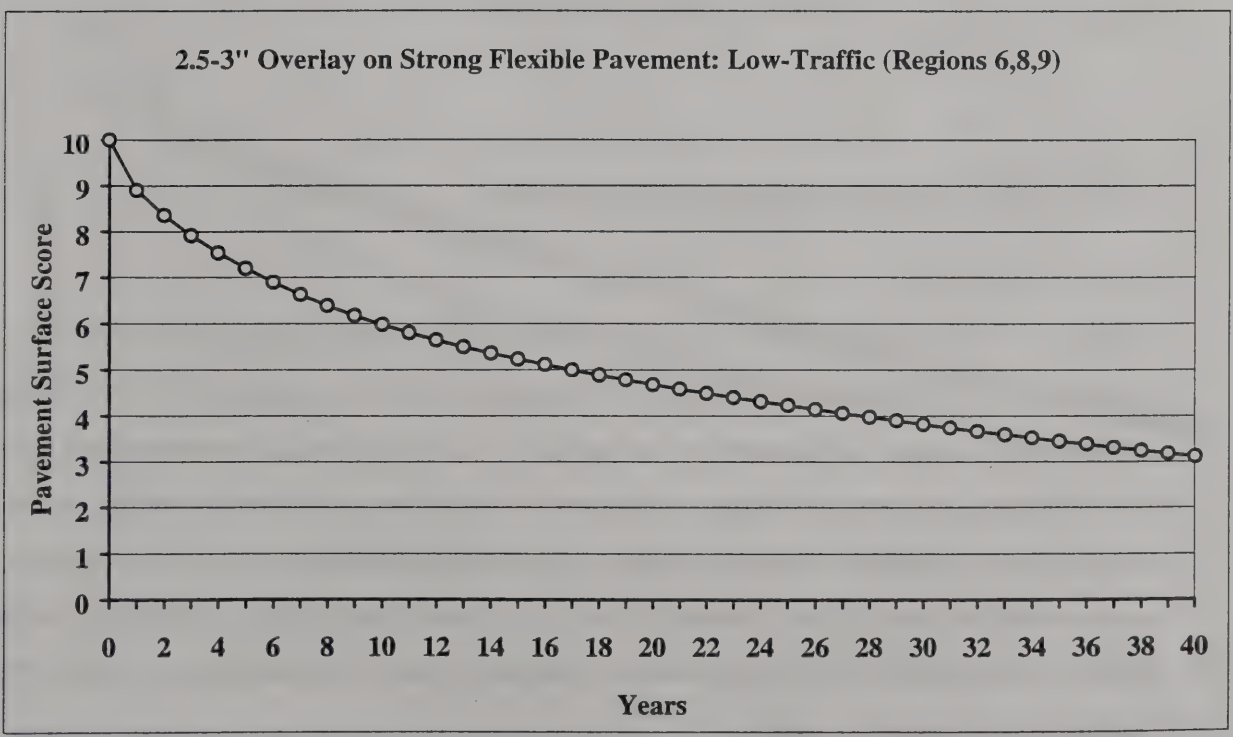

Figure B- 4.2: Average Performance Curve for a Flexible Pavement

These probabilities give us the likelihood that a pavement section will change from one surface condition to another in one year. For example, the top-left number in the matrix (0.1421) is the probability that a pavement of this category which starts with surface score of 10 will remain with the same surface score after one year. The second number, 0.6130 is the probability that the same pavement will deteriorate to surface score 9 in one year if it starts with a score of 10. On average, however, if this pavement starts with a score of 10, it is expected to have a score of 8.9 (i.e., 10*0.1421 + 9*0.9130 +8*0.2448). These average pavement scores were used to draw the average performance curve in Figure B- 4.2.

The preceding discussion of the need to categorize pavements was based on the hypothesis that different pavement categories will deteriorate differently. The following sections presents a comparison of pavement performances among the various categories. To facilitate this comparison, average performance curves, similar to one shown in Figure B- 4.2 will be used. This comparison will test the hypothesis that factors such as geographical location (region), pavement type, pavement strength, traffic loading and treatment type, have influence on the distress performance of pavements in New York State.

4.4.1 Regional Variation in Pavement Performance

Flexible Pavements

To check whether distress models need to be differentiated by regions, performance models for pavements with similar characteristics were compared across the regions. New York State was divided into 5 zones, as discussed in Section 4.3.1. As far as flexible pavements are concerned, it is evident that there are distinct variations in pavement performance among these zones. Figures B-4.3(a) and (b) show that there is a significant difference in the deterioration rates of reconstructed or new flexible pavements among regions. These figures show, for example, that strong, reconstructed flexible pavements in regions 1 and 2 deteriorate at slower rates than pavements in regions 3, 4, and 5.

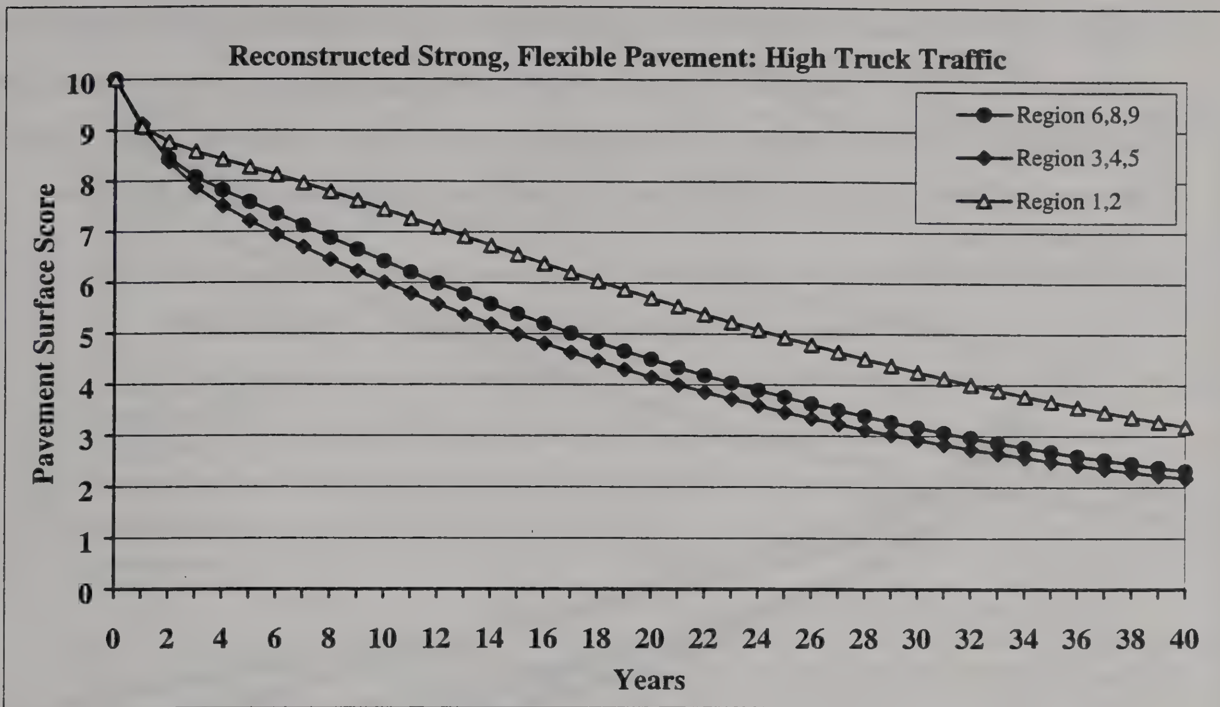

Figure B- 4.3 (a) Regional Comparison of New (or Reconstructed) Flexible Pavements

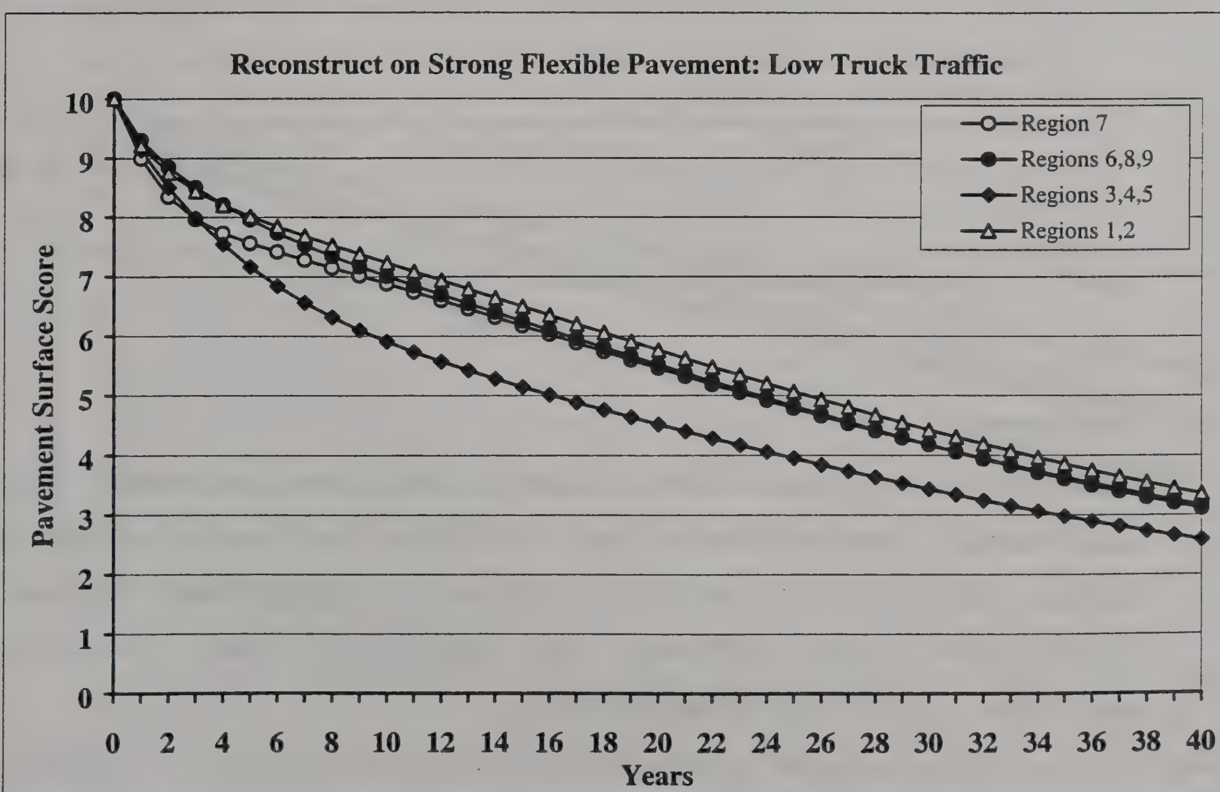

Figure B- 4.3 (b) Regional Comparison of New (or Reconstructed) Flexible Pavements

Figure B- 4.3 (c) also shows regional differences in the deterioration of flexible pavements overlaid with 2.5-3" of asphalt. It is also evident that pavements in regions 1 and 2 perform better than those in other regions. Other categories of flexible pavements show similar trends. This shows that it is important to differentiate pavement performance models by region.

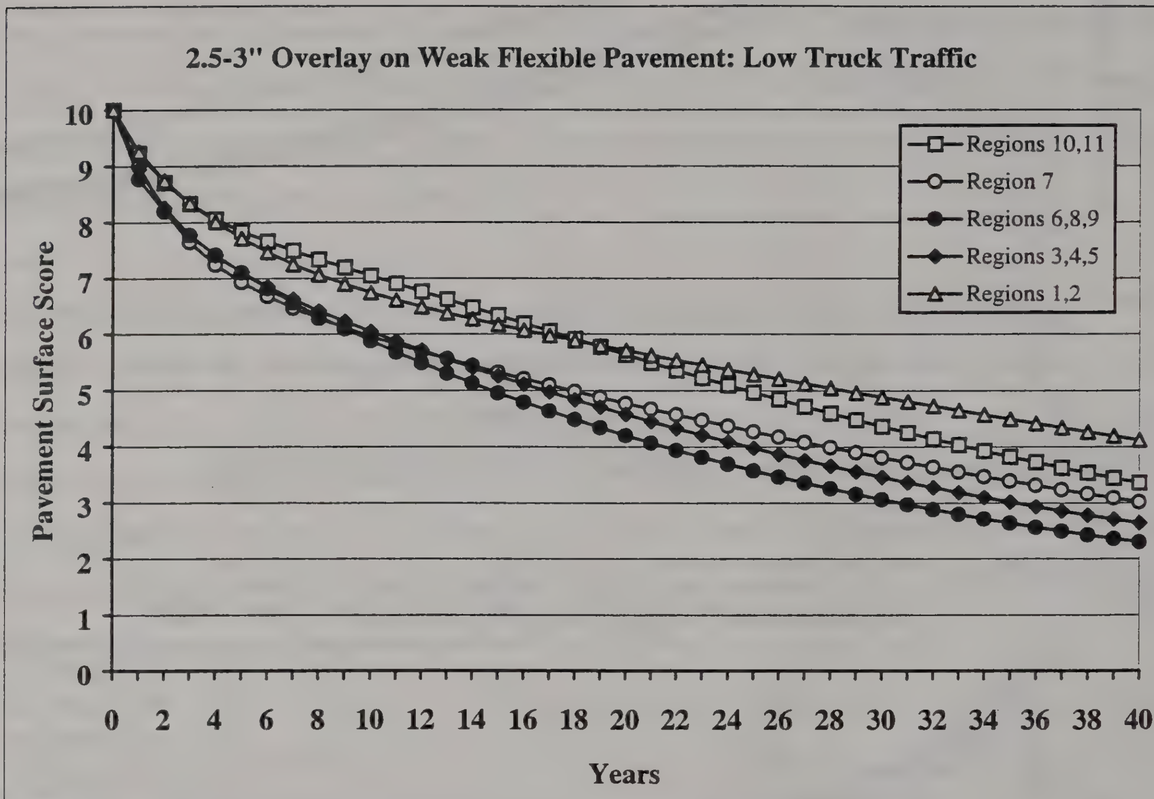

Figure B- 4.3 (c) Regional Comparison of 2.5 - 3" Overlaid Flexible Pavements

Rigid Pavements

Figures B-4.4 (a) to (c) show regional variation of rigid pavement performance. Again, it is evident that rigid pavements in regions 1 and 2 perform better than those in other regions in New York state. Figure B- 4.4 (b) shows that new or reconstructed rigid pavements in regions 10 and 11 tend to have the worst performance in the state. All this speaks in favor of regional categorization of pavement performance models.

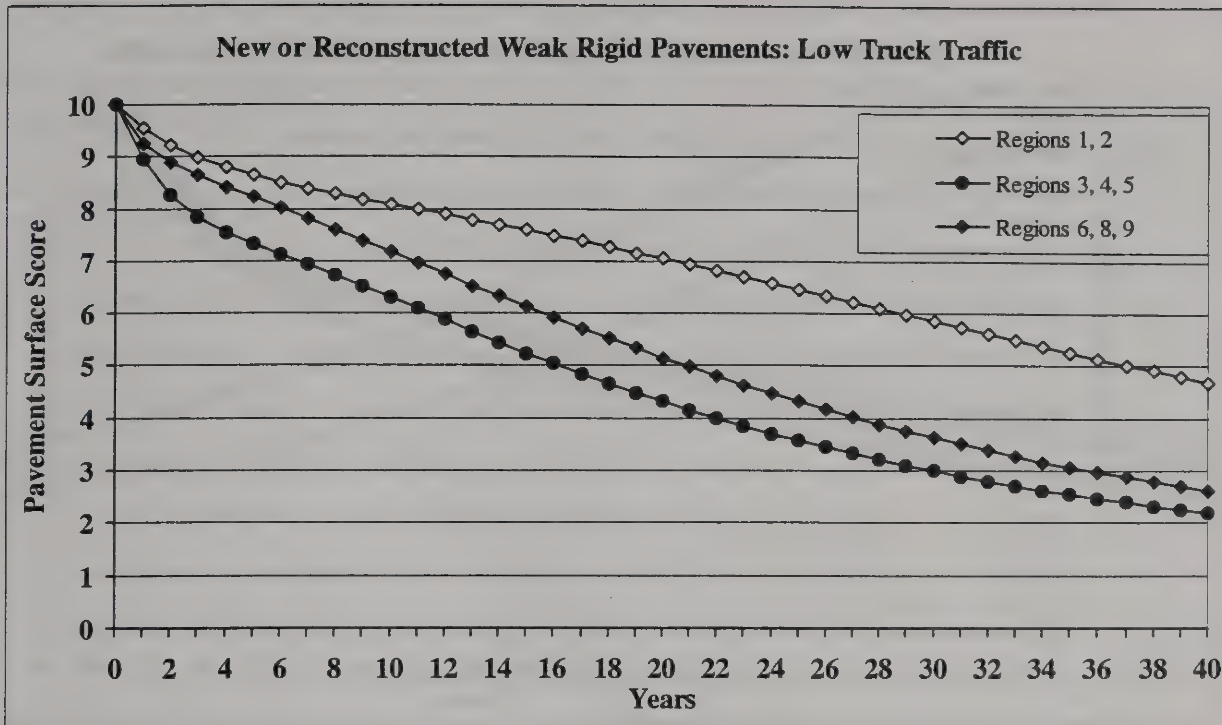

Figure B- 4.4 (a) Regional Variation in Rigid Pavement Performance: Weak Pavements with Low Truck Traffic.

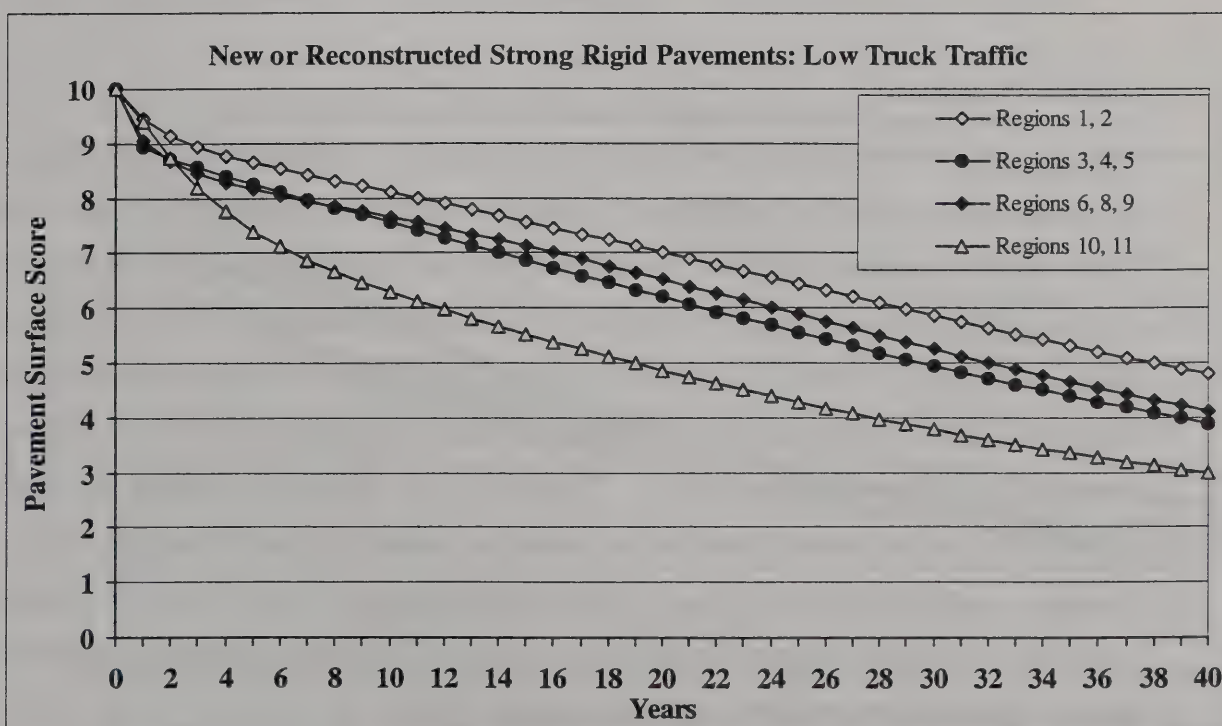

Figure B- 4.4 (b) Regional Variation in Rigid Pavement Performance: Strong Pavements with Low Truck Traffic.

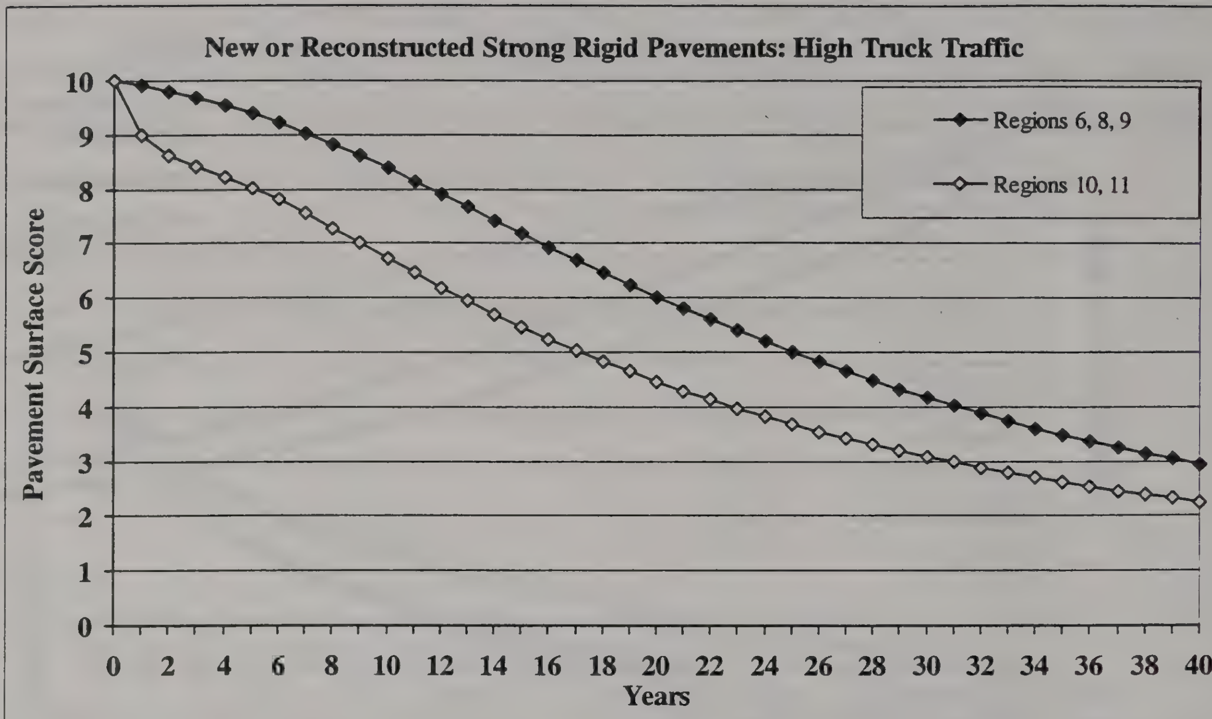

Figure B- 4.4 (c) Regional Variation in Rigid Pavement Performance: Strong Pavements with High Truck Traffic.

Overlaid Pavements

Regional variability was also observed in the performance of overlaid pavement. Figures B-4.5 (a) to (c) are examples of performance models of specific categories of overlaid pavements. There was no consistent indication of regions with better performing overlaid pavements as was the case with flexible and rigid pavements. This can be attributed to the fact that the underlying layers of overlaid pavements (old rigid pavements) had previous distresses which are randomly distributed across the regions and state. These old underlying distresses are then reflected as new distresses on the overlaid pavements. Therefore, they show no consistent regional trends. However, it can be noticed that for reconstructed pavements (see Figure B- 4.5 c), where intensive rehabilitation work is done to the underlying rigid pavement layer, the trend observed in flexible and rigid pavement is also seen in overlaid pavement, namely that pavements in regions 1 and 2 outperform those in other regions.

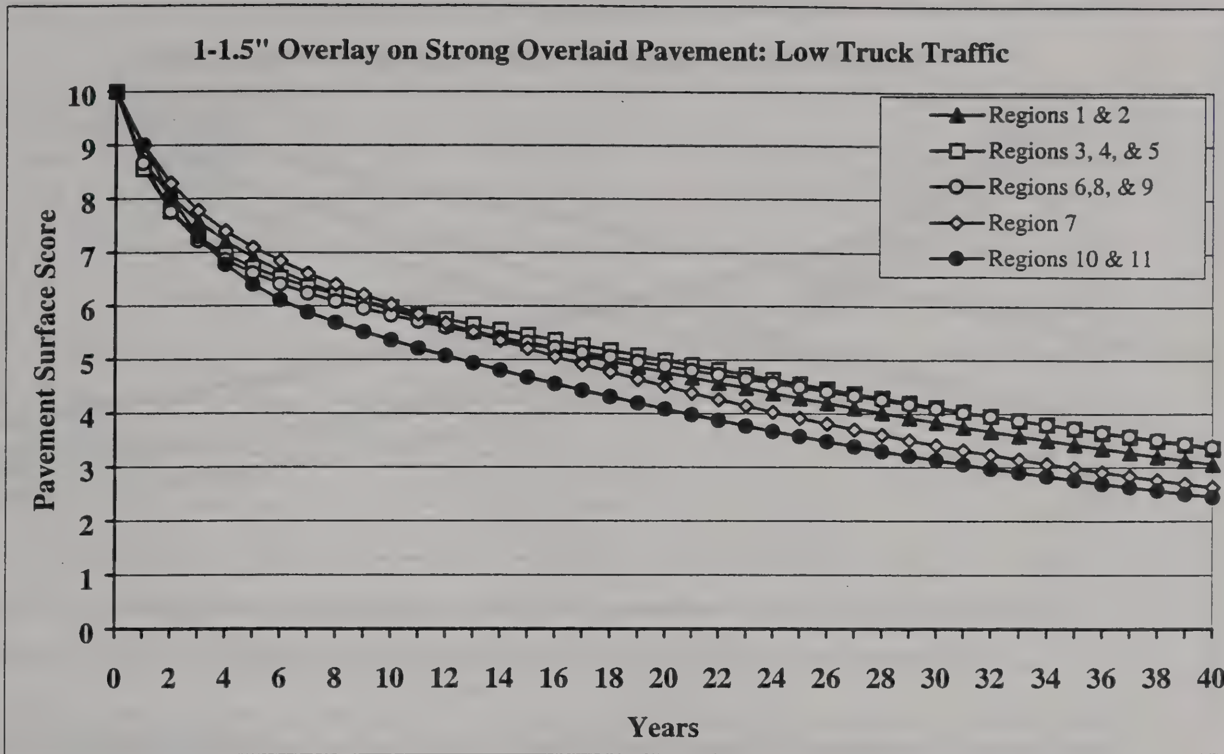

Figure B- 4.5 (a) Performance of Strong Overlaid Pavements: 1-1.5" Overlay with Low Truck Traffic

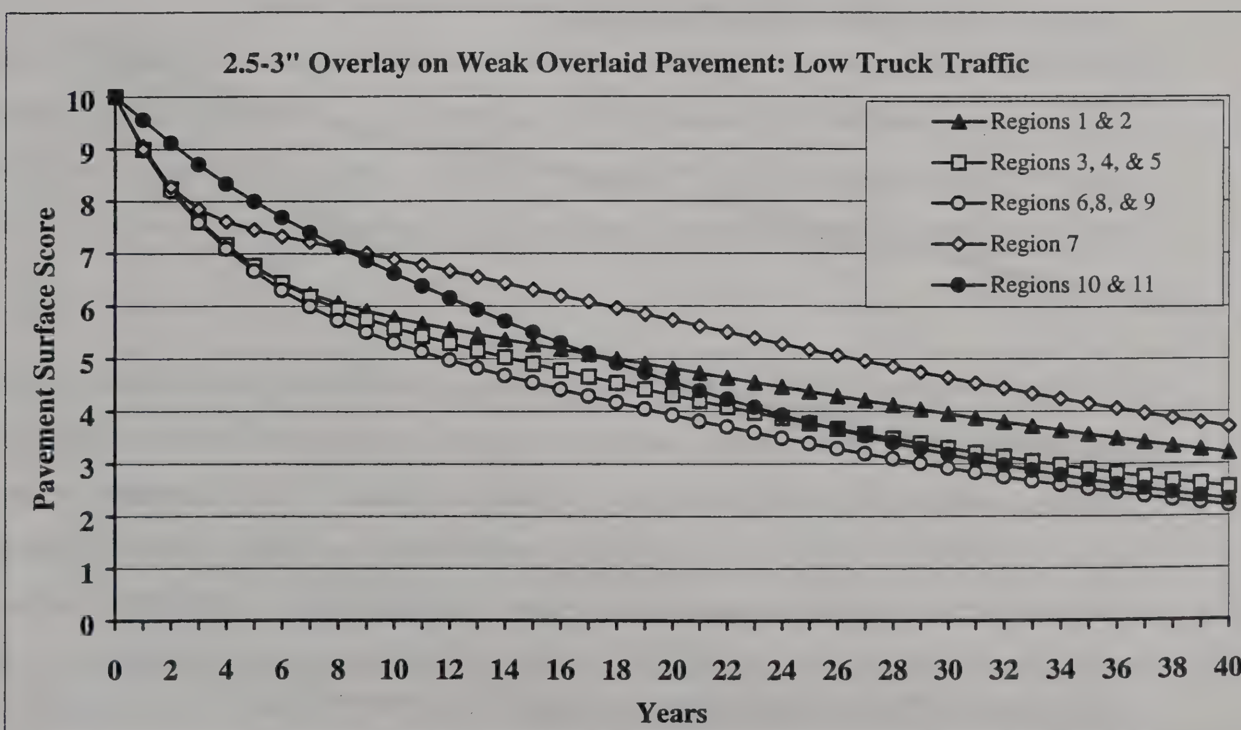

Figure B- 4.5 (b) Performance of Strong Overlaid Pavements: 2.5-3" Overlay with Low Truck Traffic

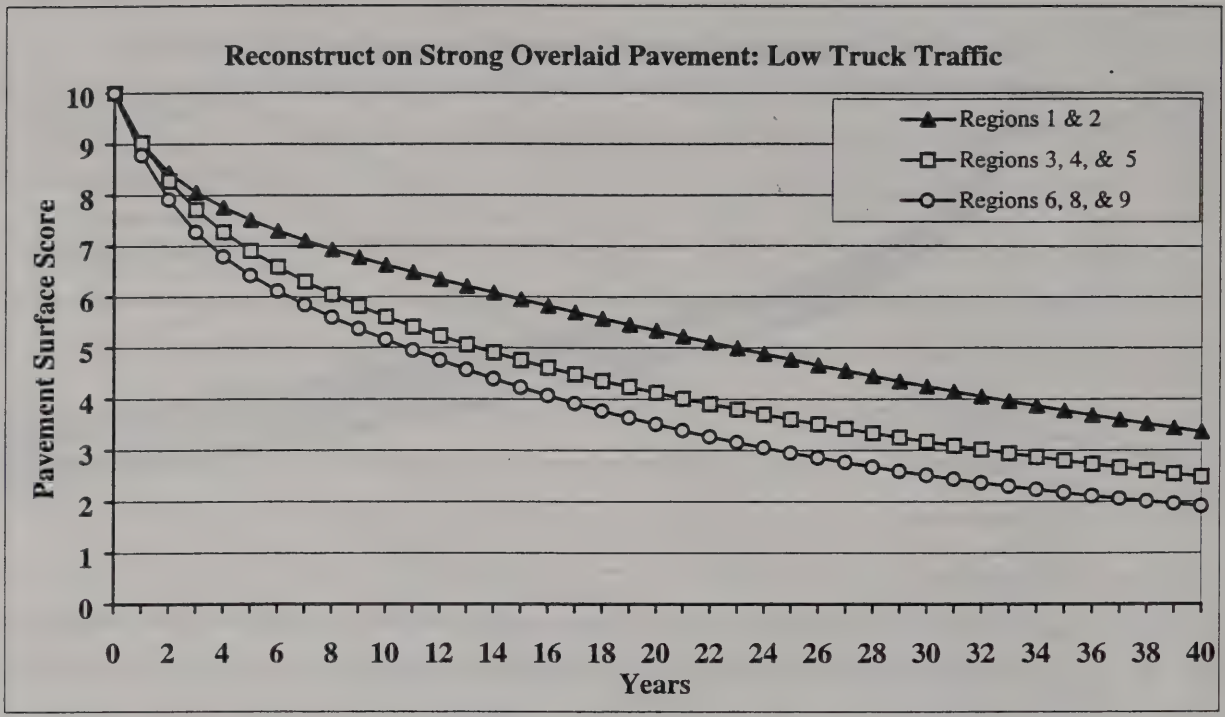

Figure B- 4.5 (c) Performance of Strong Overlaid Pavements: Reconstructed Pavement with Low Truck Traffic

4.4.2 Effect of Pavement Type on Performance

One of the factors used to categorize pavements is pavement type (i.e., flexible, overlaid, and rigid). To see the effect of pavement type on performance, curves of the three pavement types were compared by region, pavement strength and traffic loading. This comparison is done for new or reconstructed pavements only because this is the treatment type common to all three pavement types.

As shown in Figures B-4.6 (a) to (d), rigid pavements consistently perform better than flexible and overlaid pavements for all pavement sub-categories. It can also be seen in these figures that flexible pavements performed better than overlaid pavements. This observation was expected because overlaid pavements are old rigid pavements with an asphalt-concrete overlay. The distresses of the old rigid pavements quickly show up after treatment as reflection cracks. This is not the case with flexible pavements. These observations confirm the need to categorize pavements by type when modeling performance.

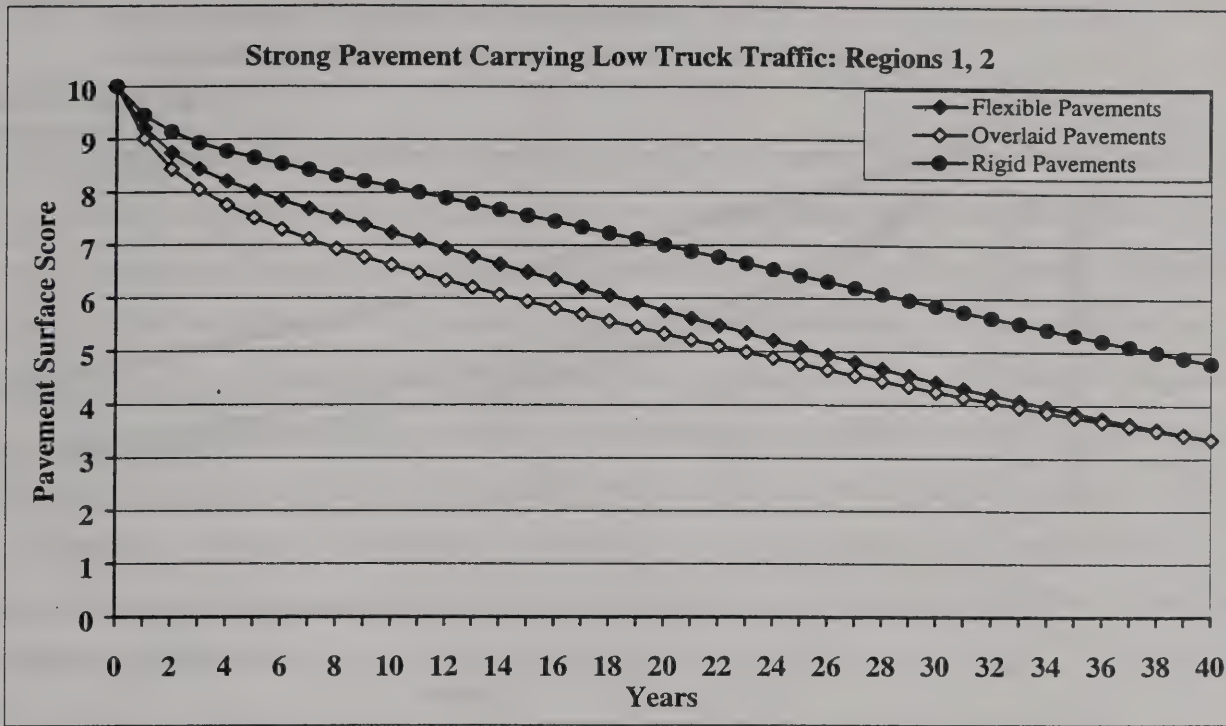

Figure B- 4.6 (a) Effect of Pavement Type: Strong Pavements with Low Truck Traffic - Regions 1 & 2.

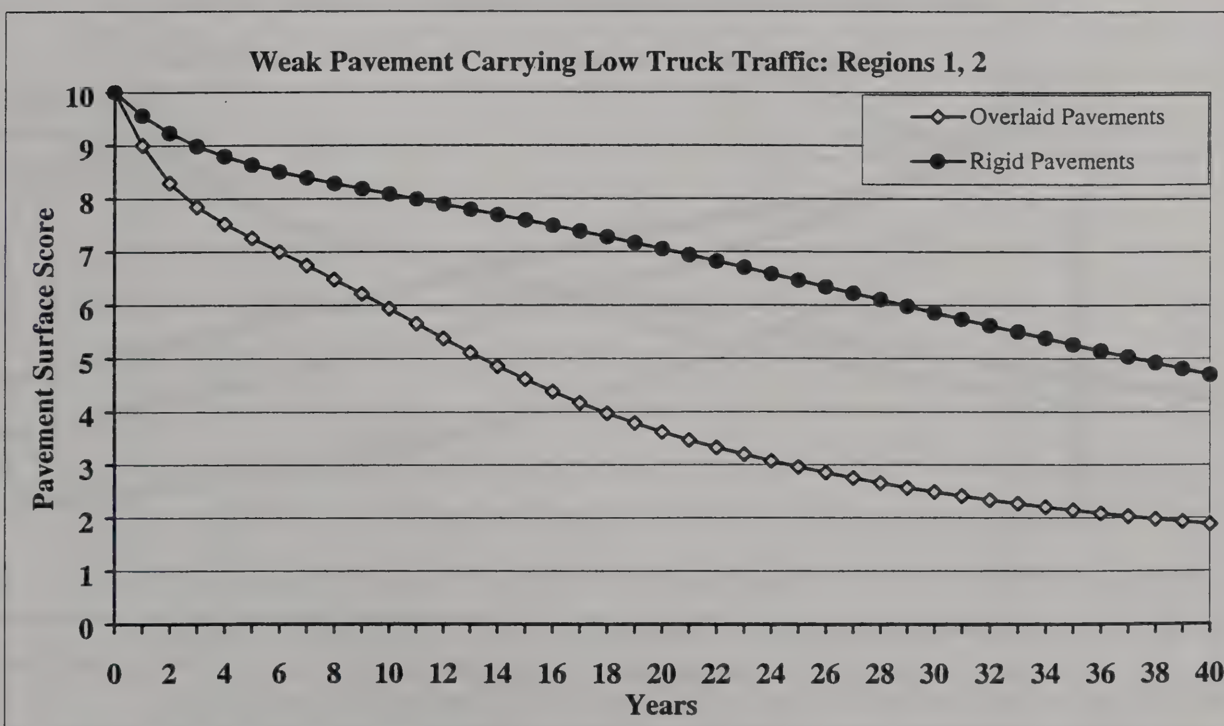

Figure B- 4.6 (b) Effect of Pavement Type: Weak Pavements with Low Truck Traffic - Regions 1 & 2.

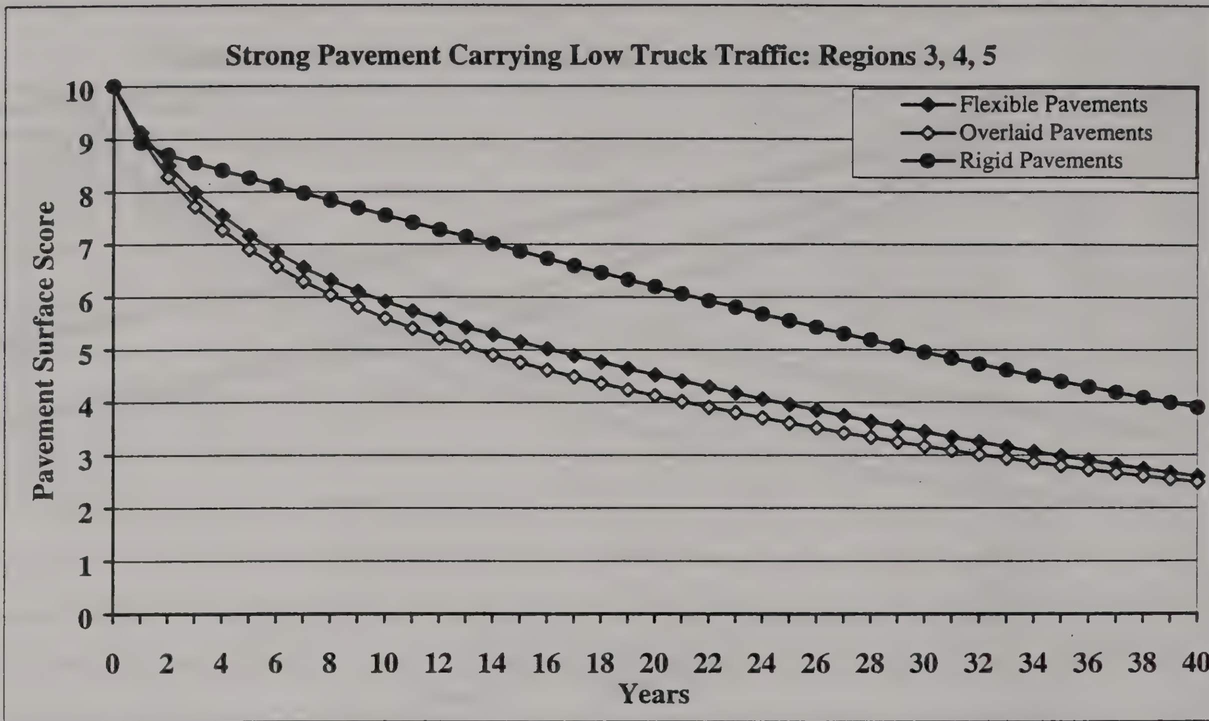

Figure B- 4.6 (c) Effect of Pavement Type: Strong Pavements with Low Truck Traffic - Regions 3, 4, & 5.

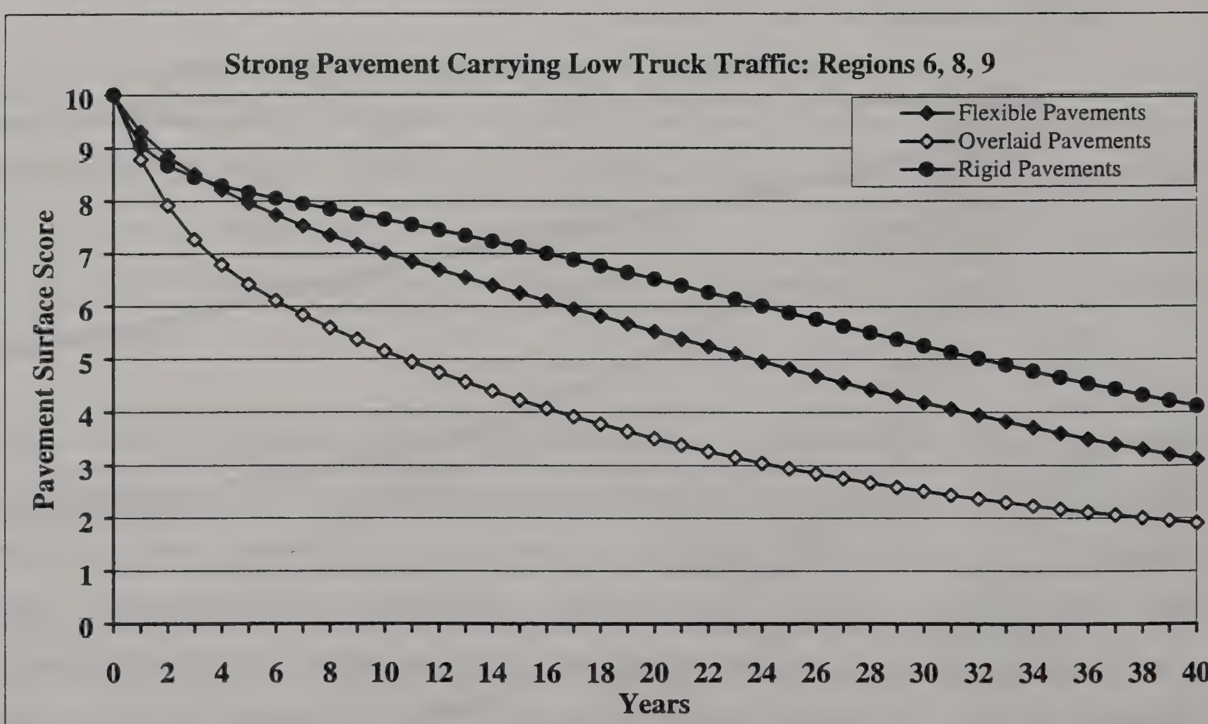

Figure B- 4.6 (d) Effect of Pavement Type: Strong Pavements with Low Truck Traffic - Regions 6, 8, & 9.

4.4.3 Effect of Pavement Strength on Performance

Flexible Pavements

It was hypothesized that pavement deterioration will be influenced by the structural capacity of pavements. Pavements were then grouped into two strength categories: Strong and Week. This categorization was based on the surface, base, and sub-base types used, as discussed in Section 4.3.3. From the performance estimation results, it is not evident that this categorization has a significant effect on flexible pavement deterioration. Figures B-4.7 (a) to (f) compares regional performance curves for flexible pavements by their strength categories and it is not evident (at least for the categories that were estimated) that strength categories play a significant role in differentiating pavement performance. However, it is recommended that categorization by pavement strength be maintained in performance modeling. With time this effect should be monitored and updated.

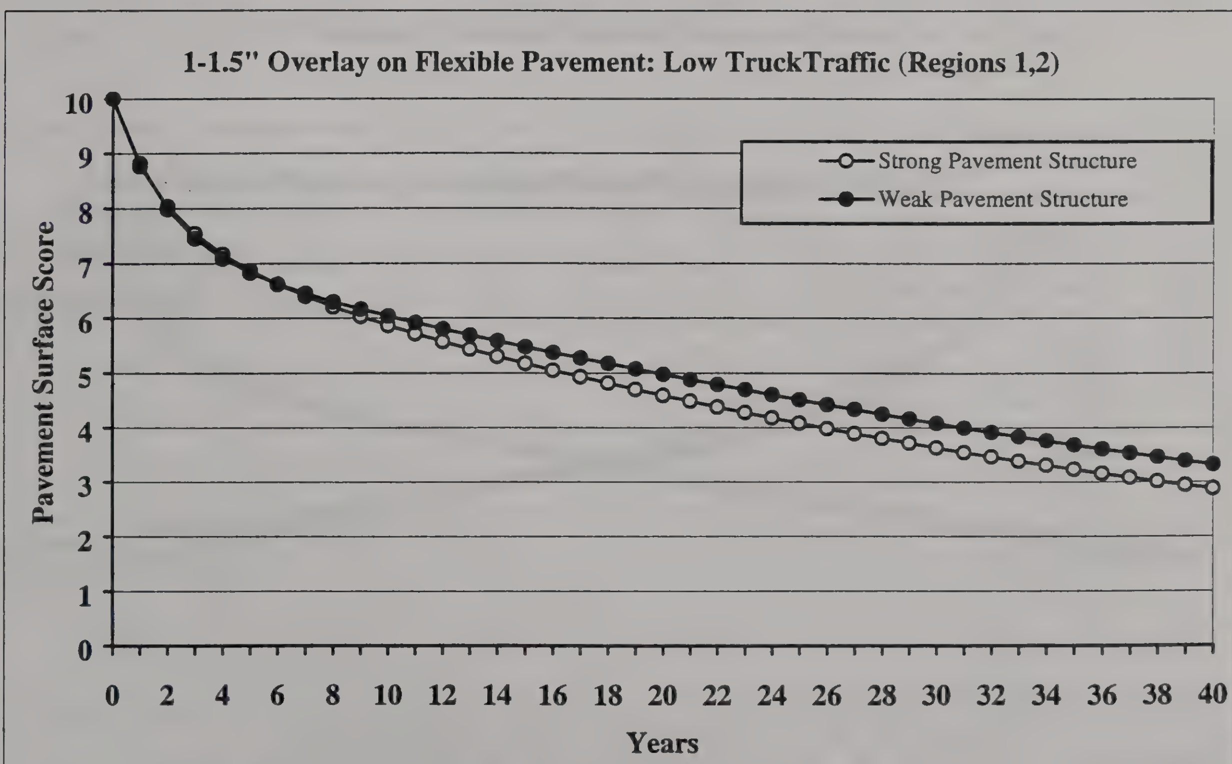

Figure B- 4.7 (a) Effect of Strength on Pavement Performance - Regions 1 & 2.

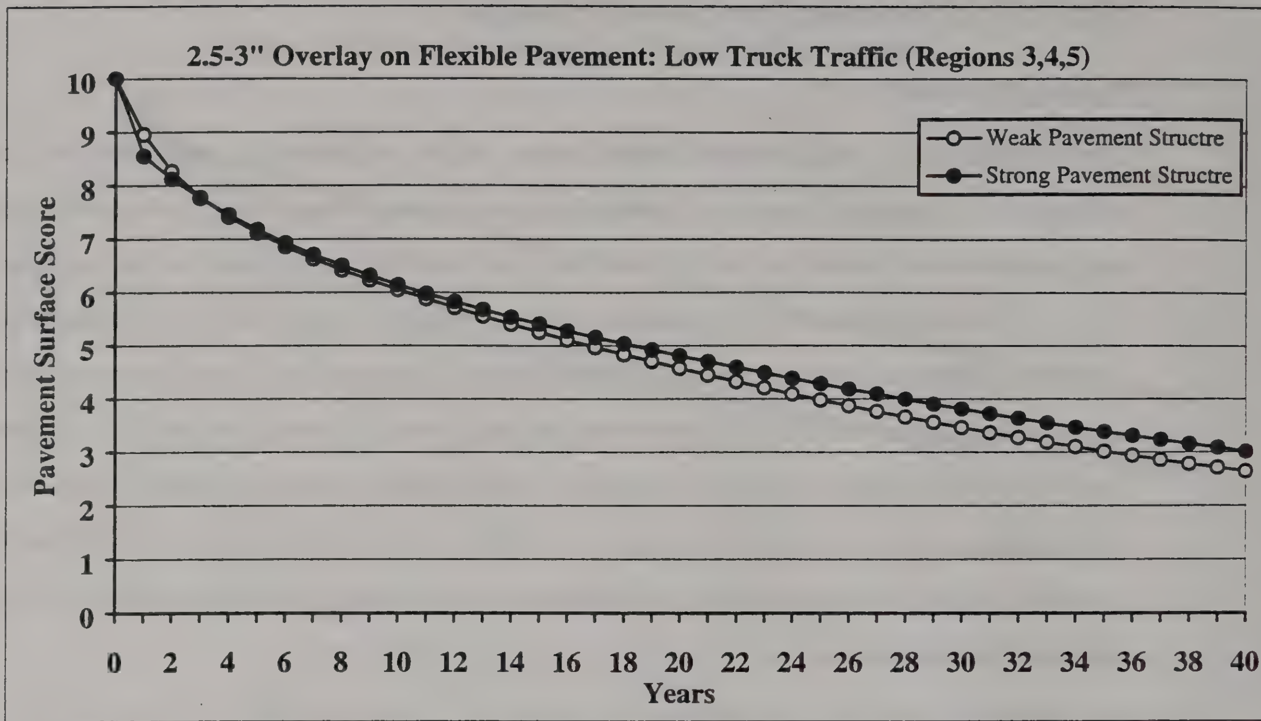

Figure B- 4.7 (b) Effect of Strength on Pavement Performance - Regions 3, 4 & 5.

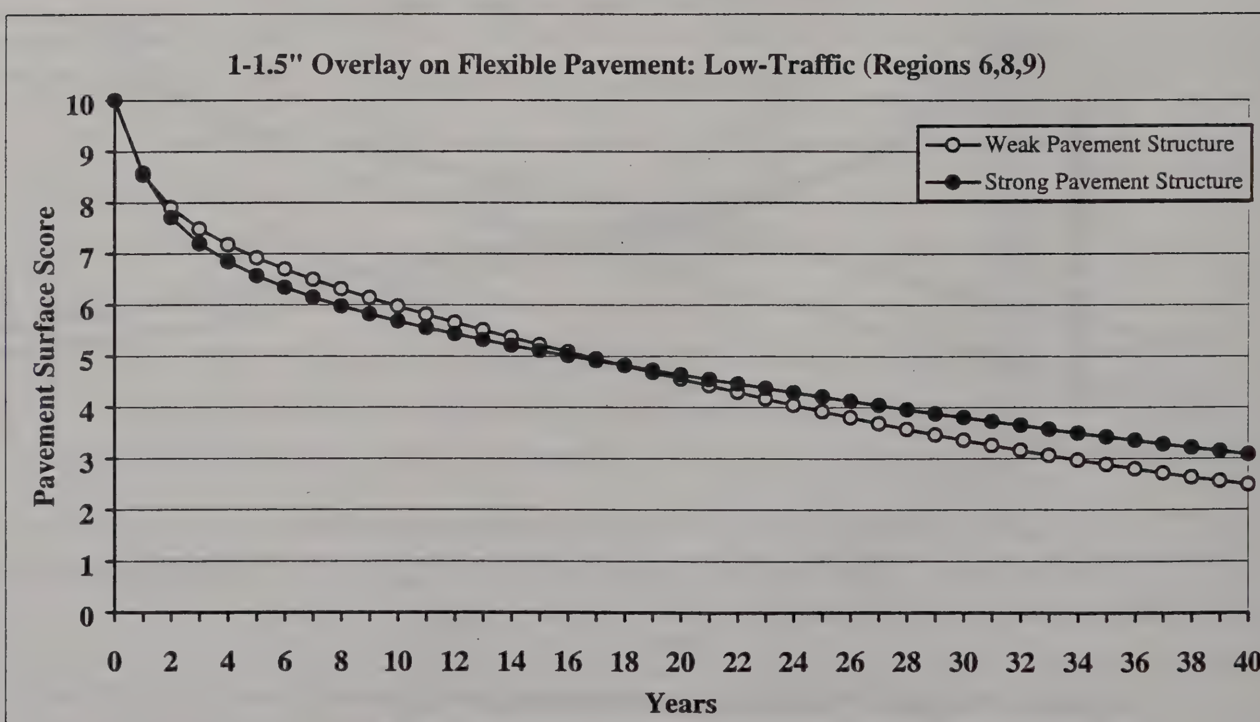

Figure B- 4.7 (c) Effect of Strength on Pavement Performance - Regions 6, 8 & 9.

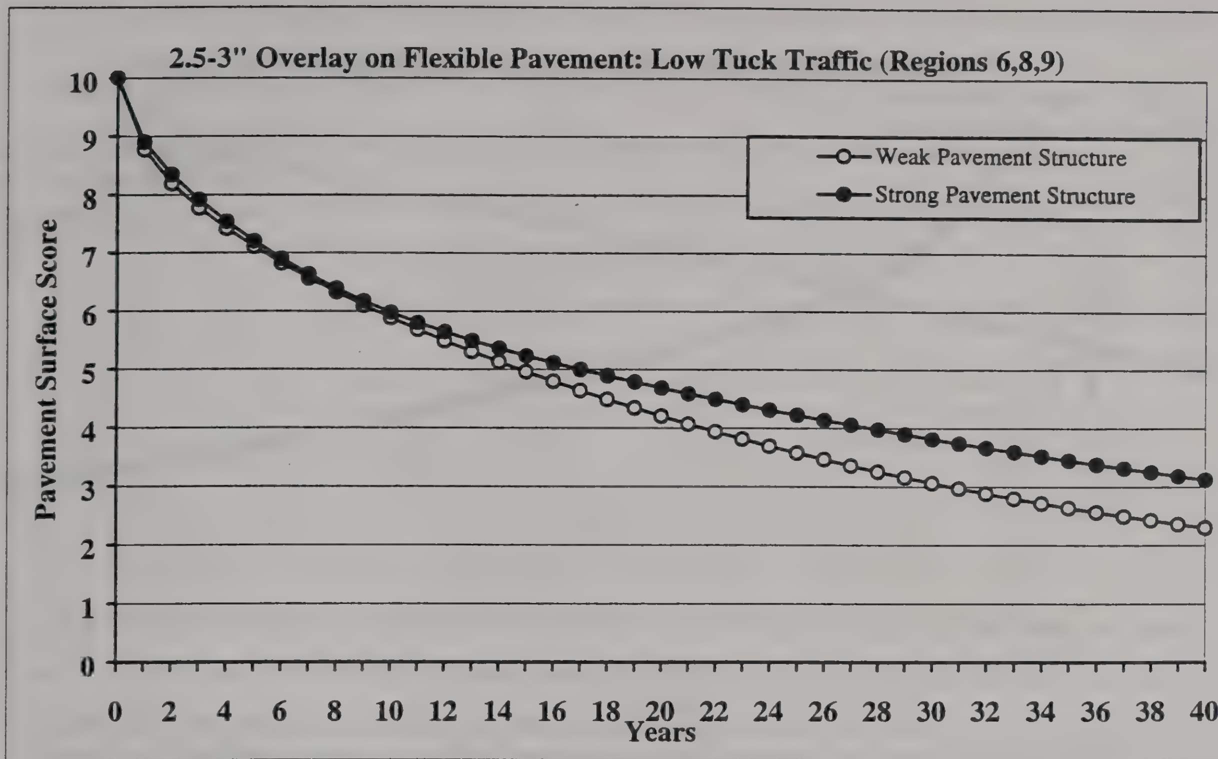

Figure B- 4.7 (d) Effect of Strength on Pavement Performance - Regions 6, 8 & 9.

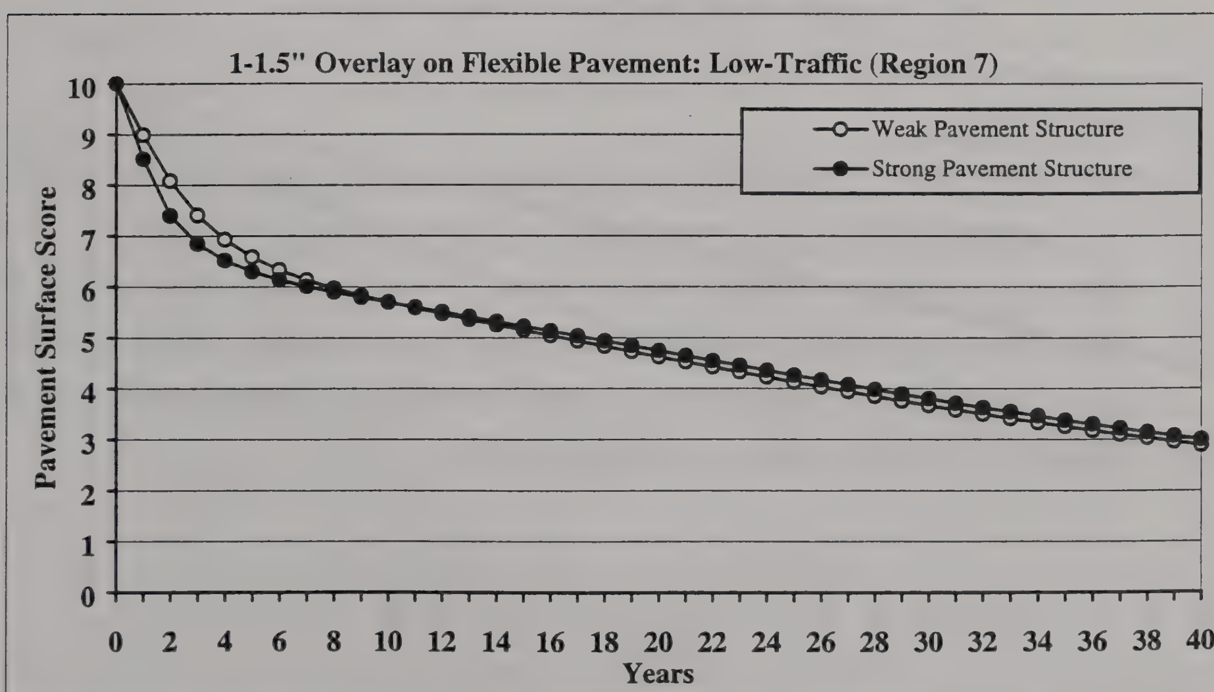

Figure B- 4.7 (e) Effect of Strength on Pavement Performance - Region 7.

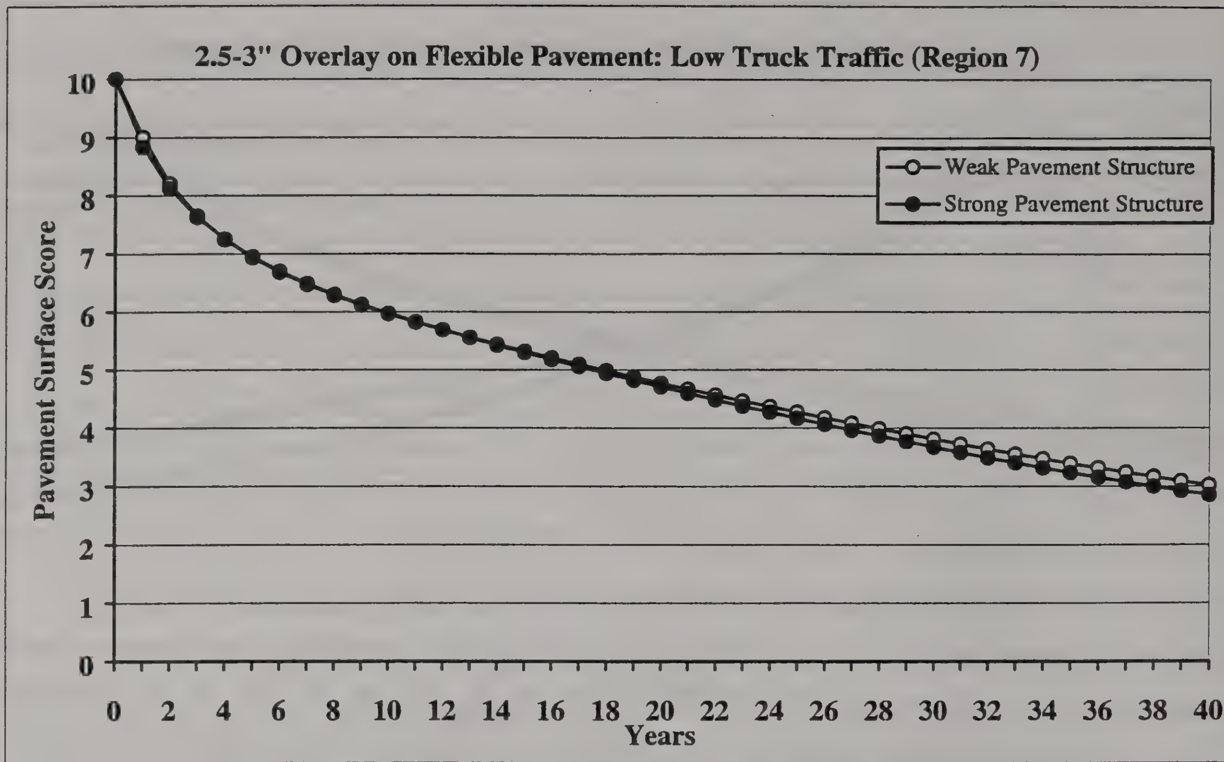

Figure B- 4.7 (f) Effect of Strength on Pavement Performance - Region 7.

Rigid Pavements

Figures B-4.8 (a) to (c) show the effect of strength on rigid pavement performance. Figure B-4.8 (a) demonstrates that rigid pavements that carry low truck traffic in regions 1 and 2 show no difference in performance between weak and strong. However, regions 3 to 6, 8 and 9, pavement strength show significant effect on the performance of rigid pavements. Figures B-4.8 (b) and (c) demonstrate this effect. This confirms the need to categorize rigid pavements by their structural strength in order to get consistent performance models.

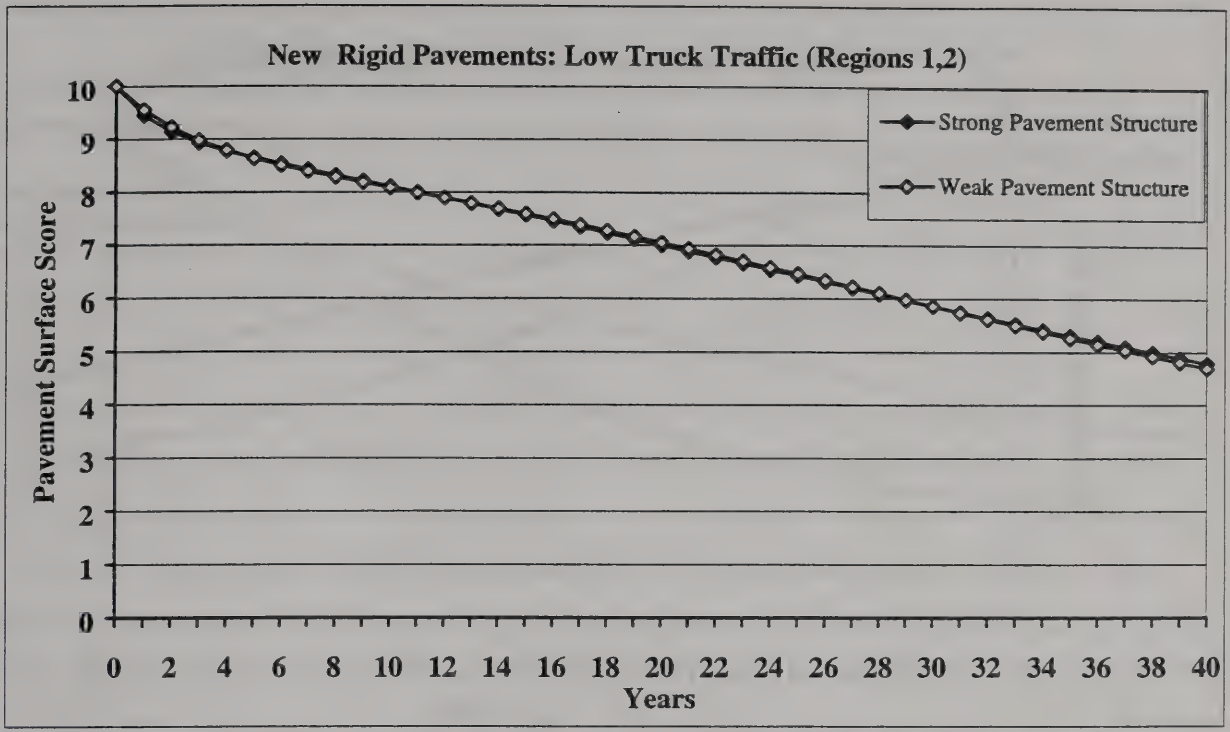

Figure B- 4.8 (a) Effect of Strength on Performance of Rigid Pavements: Low Traffic Loading in Regions 1 & 2.

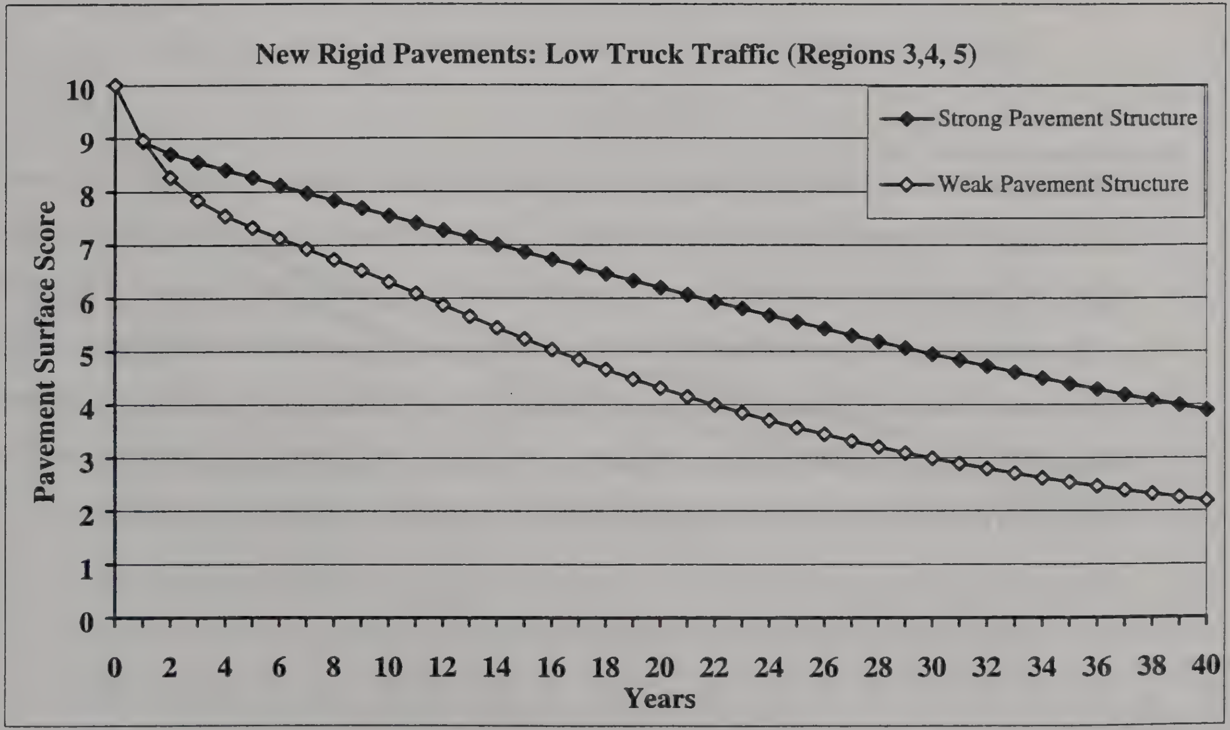

Figure B- 4.8 (b) Effect of Strength on Performance of Rigid Pavements: Low Traffic Loading in Regions 3, 4, & 5

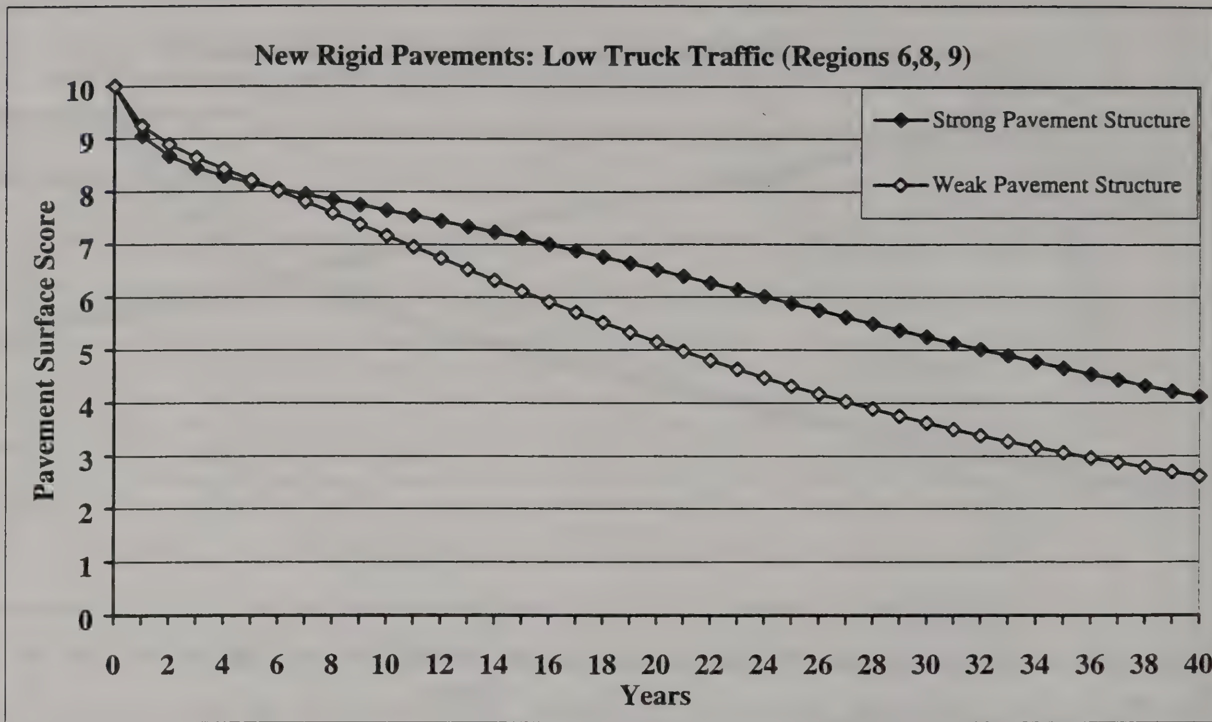

Figure B- 4.8 (c) Effect of Strength on Performance of Rigid Pavements: Low Traffic Loading in Regions 6, 8, & 9

Overlaid Pavements

Overlaid pavements were also categorized in terms of their strength. Section 4.3.3 discusses the criteria used to determine pavement strength. Figures B-4.9 (a) to (e) show examples of the effect of strength on overlaid pavement performance. Figure B- 4.9 (a) shows a large difference in the performance of reconstructed, low trafficked overlaid pavements in regions 1 and 2. This difference, however, is seen more in later years of the life of these pavements than in the first 5 to 10 years. The rest of these curves (Figures B-4.9 (b) to (e)) show that, while strong pavements have better performance than weak pavements, the effect of strength is not significant.

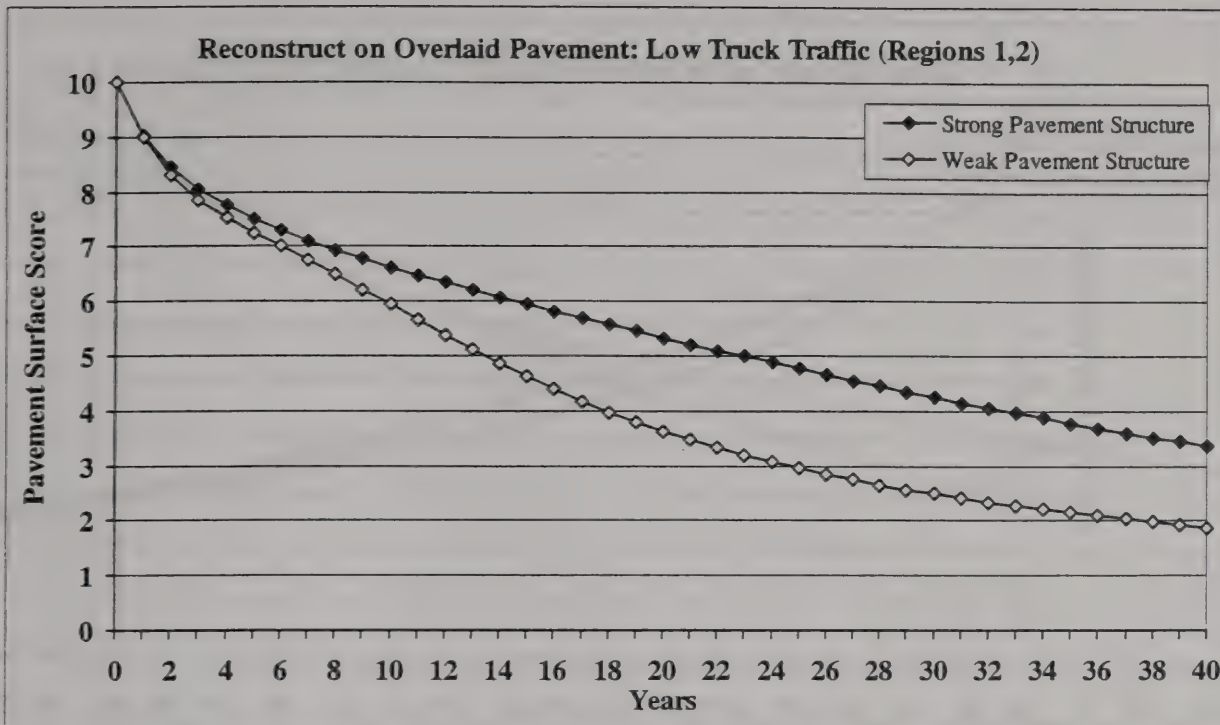

Figure 3- 4.9 (a) Effect of Strength: Reconstructed Overlaid Pavements with Low Truck Traffic - Regions 1 & 2.

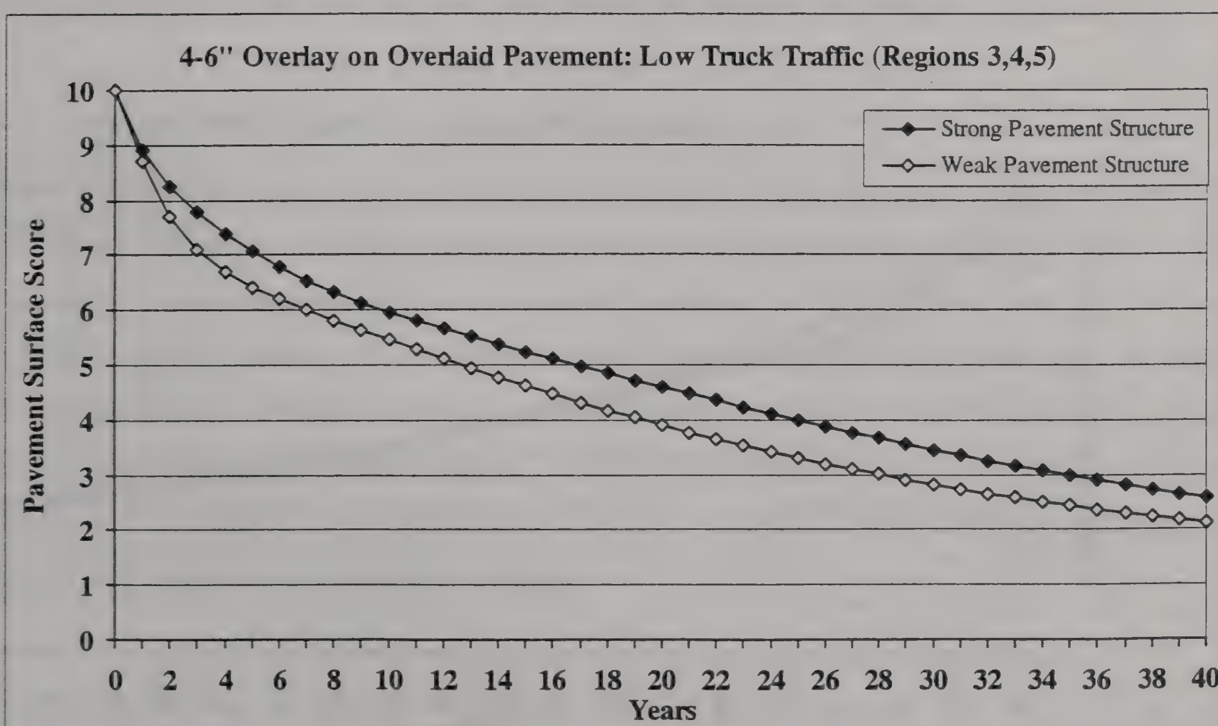

Figure B- 4.9 (b) Effect of Strength: 4-6" Overlaid Pavements with Low Truck Traffic - Regions 3, 4, & 5.

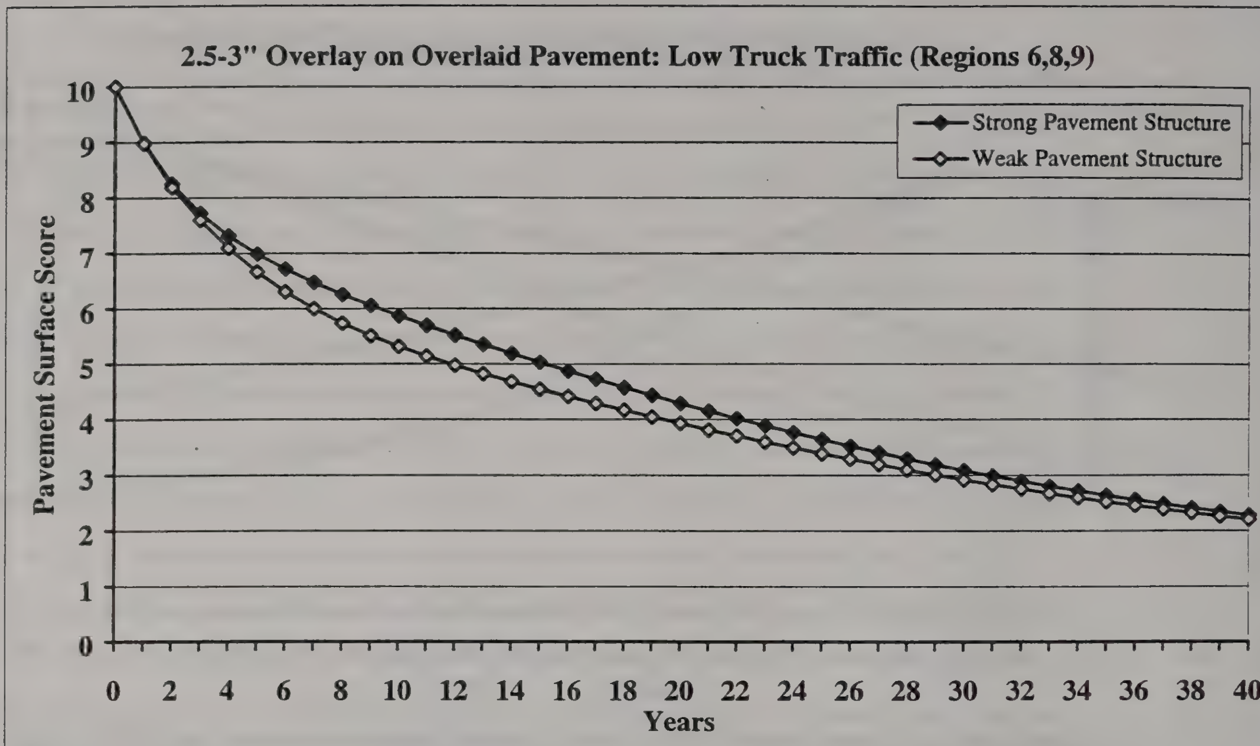

Figure B- 4.9 (c) Effect of Strength: 2.5-3" Overlaid Pavements with Low Truck Traffic - Regions 6, 8, & 9.

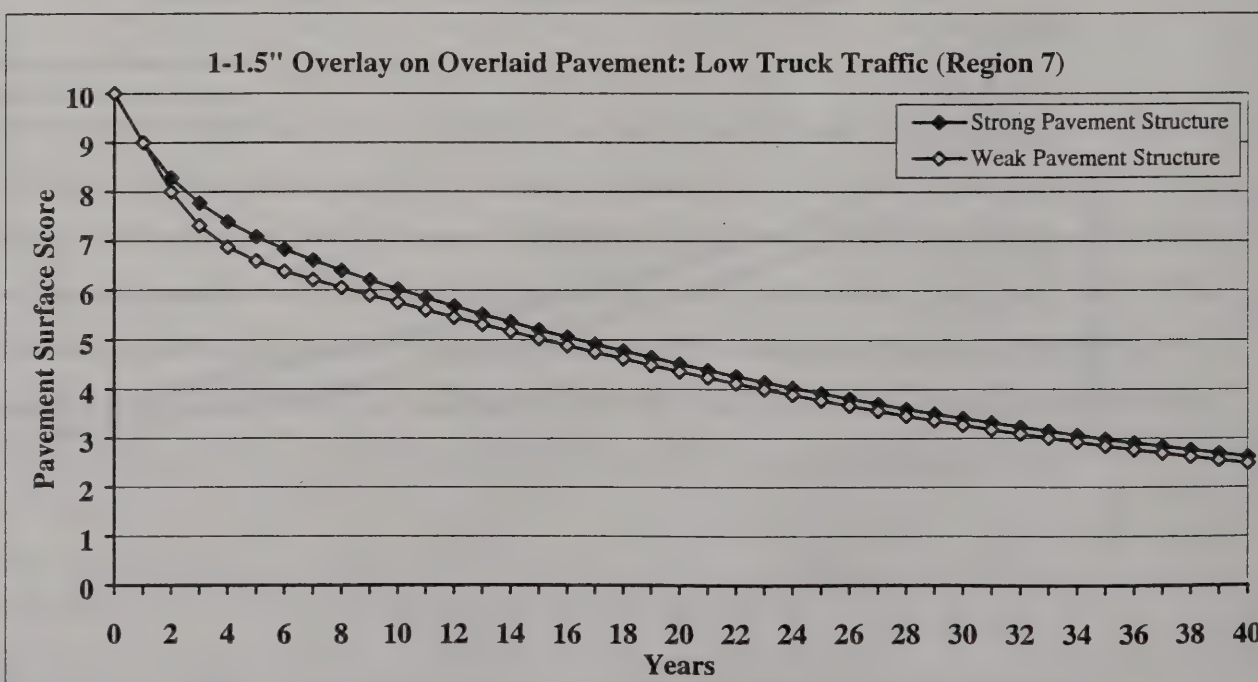

Figure B- 4.9 (d) Effect of Strength: 1-1.5" Overlaid Pavements with Low Truck Traffic - Region 7.

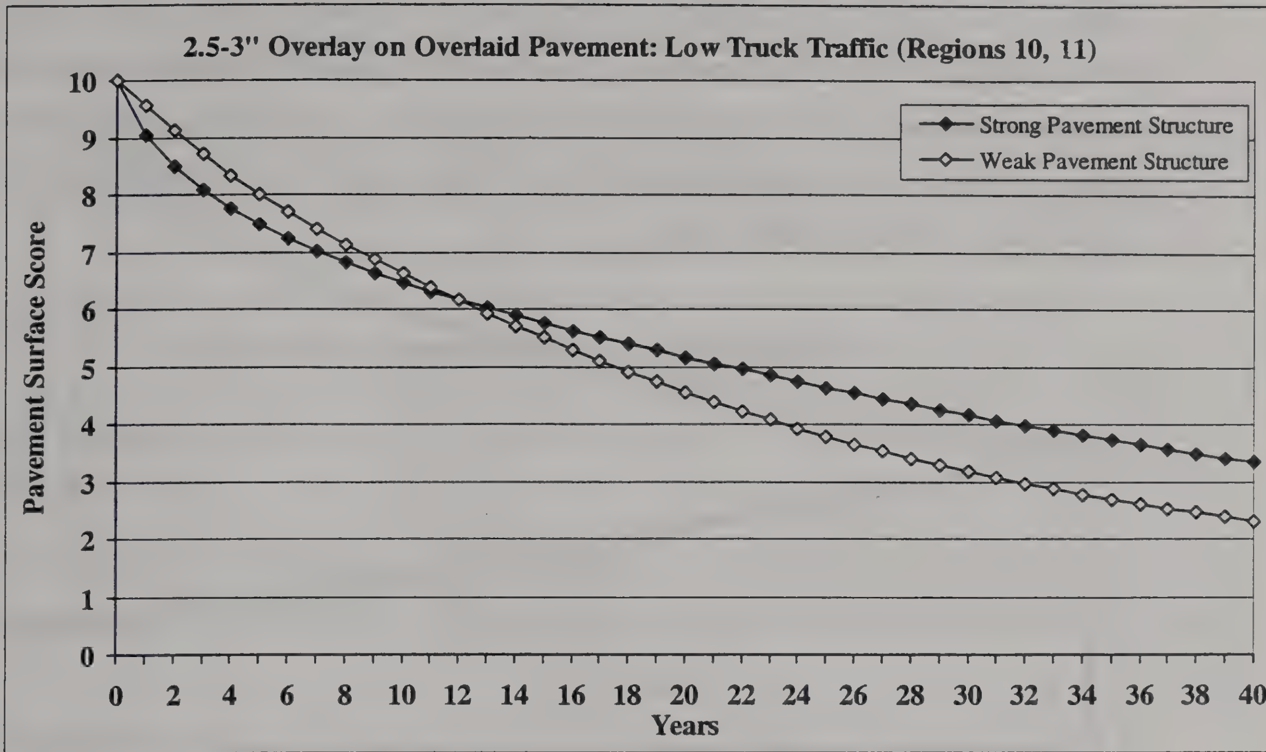

Figure B- 4.9 (e) Effect of Strength: 2.5-3" Overlaid Pavements with Low Truck Traffic - Regions 10 & 11.

4.4.4 Effect of Traffic Loading on Pavement Performance

Pavement performance depends on the type and extent of traffic loading imposed on it over its life time. Pavement structural capacity is diminished as it carries more repetitive loads. The remaining structural capacity (or remaining life) depends on the pavement's initial structural capacity and the number of equivalent standard axle loads (ESALs). Passenger cars have negligible ESALs compared to trucks. Therefore, truck traffic was used to give us a rough indication of the extent of traffic loading. Pavements carrying less than 1,000 trucks per day per lane were categorized as low traffic loading, and those carrying 1,000 or more trucks per day per lane were categorized as high traffic loading.

Flexible Pavements

From the results of performance modeling, the effect of traffic loading on flexible pavement was evident but not significant, except for those pavements in regions 6,8, and 9. Figures B-4.10 (a) to (c) show insignificant effect of traffic loading on flexible pavements in regions 1 through 5.

Figure B- 4.10 (d) shows a significant effect in regions 6,8, and 9. There was not enough data from other regions to test this hypothesis. However, traffic loading categorization is important in predicting pavement performance and it is recommended in estimating performance models. There is a need to find other ranges (instead of 1000 vpd/lane) to stratify the data in order to capture the true effect of traffic loading.

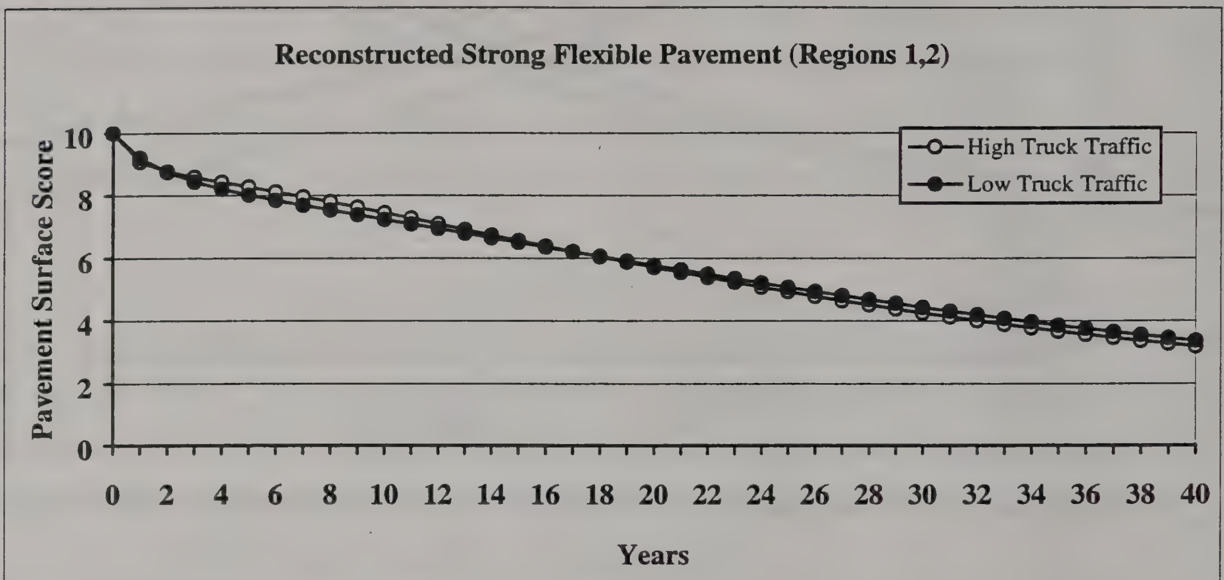

Figure B- 4.10 (a) Effect of Traffic Loading on Overlaid Pavement Performance - Regions 1&2

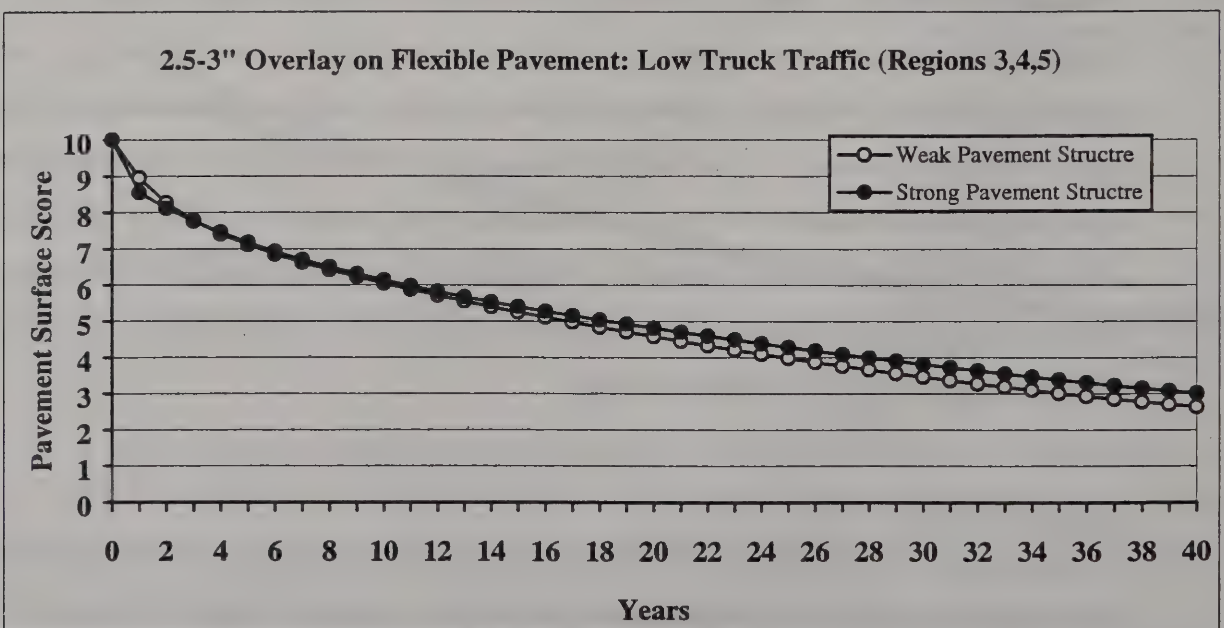

Figure B- 4.10 (b) Effect of Traffic Loading on Overlaid Pavement Performance - Regions 3,4&5

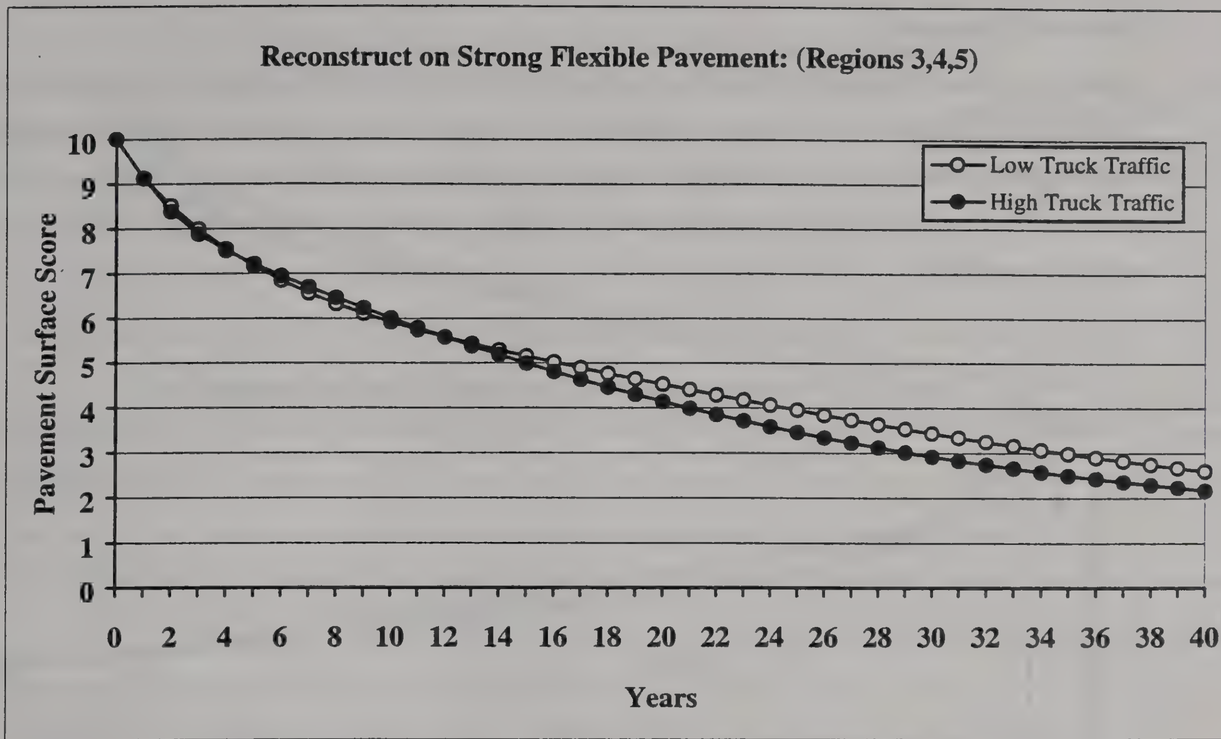

Figure B- 4.10 (c) Effect of Traffic Loading on Overlaid Pavement Performance - Regions 3,4&5

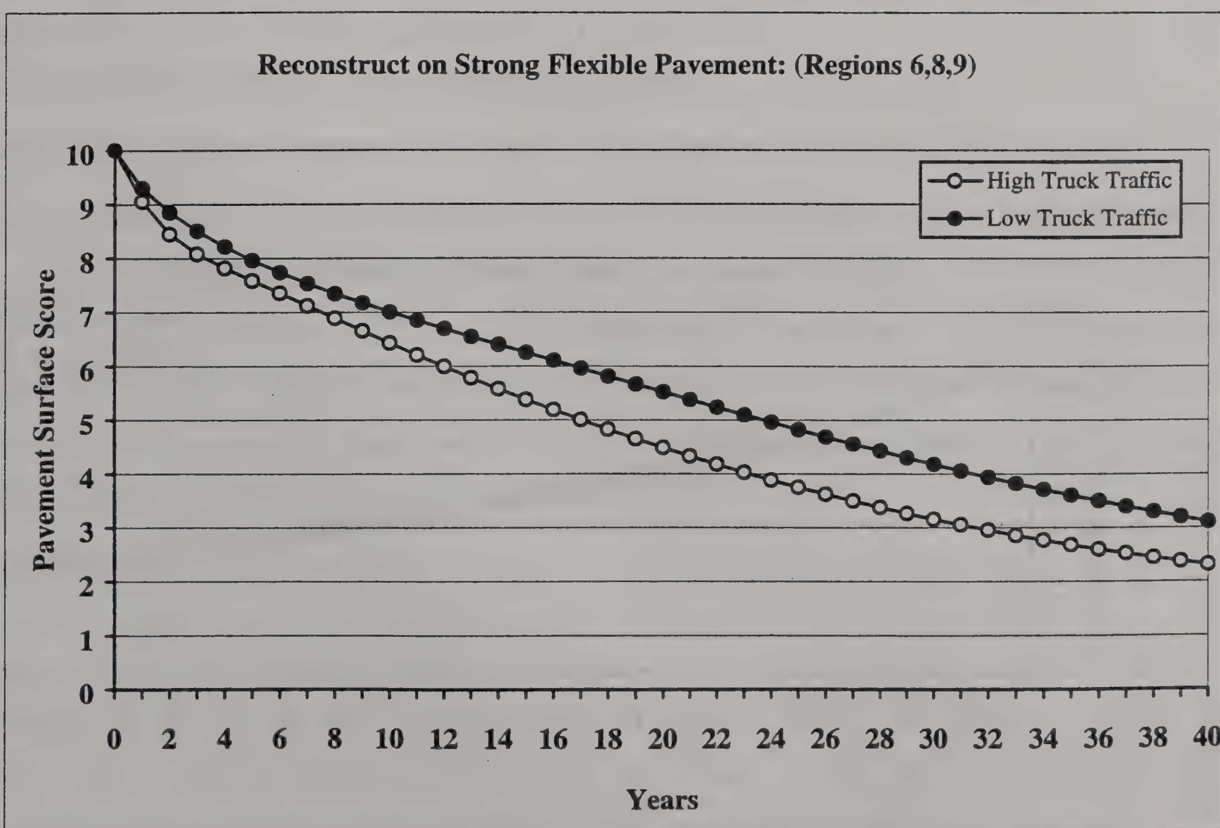

Figure B- 4.10 (d) Effect of Traffic Loading on Overlaid Pavement Performance - Regions 6,8&9

Overlaid Pavements

Unlike the case of rigid pavements, not much effect of traffic loading was observed in the performance models for overlaid pavements. Figures B-4.11 (a) to (c) show examples the insignificant effect of truck traffic volume on pavement performance. However, it is still advisable to maintain the categorization by traffic loading and that these models should be updated regularly.

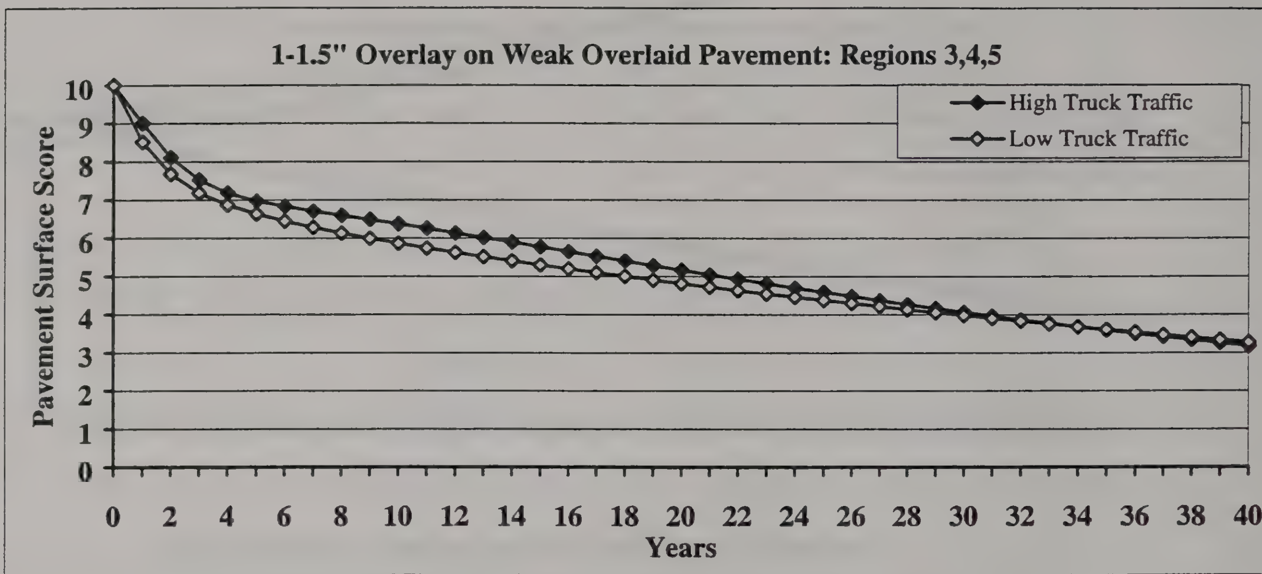

Figure B- 4.11 (a) Effect of Traffic Loading: 1-1.5" Weak Overlaid Pavements - Regions 3, 4, & 5.

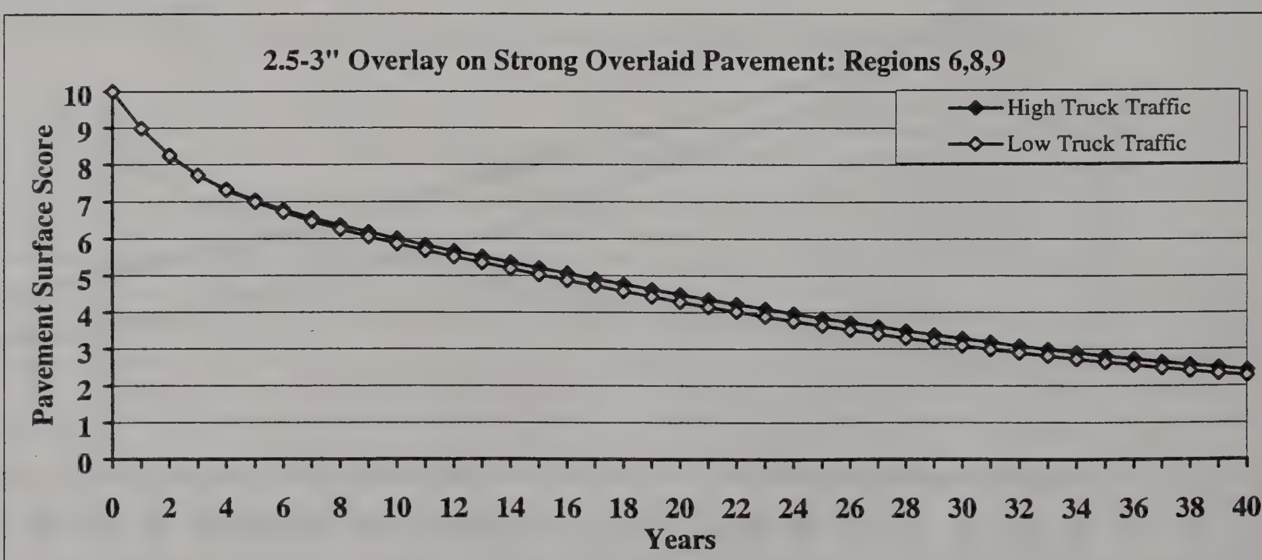

Figure B- 4.11 (b) Effect of Traffic Loading: 2.5-3" Strong Overlaid Pavements - Regions 6, 8, & 9.

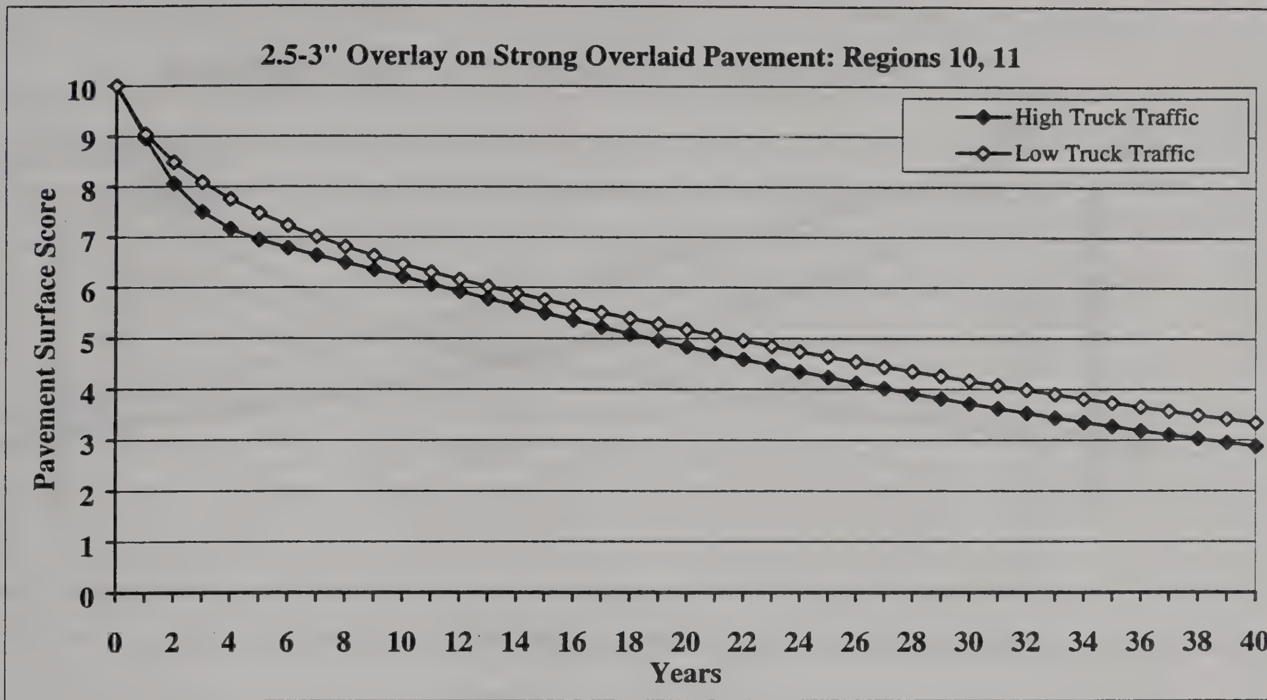

Figure B- 4.11 (c) Effect of Traffic Loading: 2.5-3" Strong Overlaid Pavements - Regions 10 & 11.

4.4.5 Effect of Treatment Type on Pavement Performance

Flexible Pavements

It is evident that the type of treatment has an effect on the deterioration rates of flexible pavements. Please note that this difference is not so pronounced between 1-1.5" overlays and 2.5-3" overlays. Figures B-4.12 (b) to (e) show that the performance curves for pavements treated by these two types of treatment are very similar. However, the performance of new or reconstructed pavements is much better and differs significantly from the other two treatments. This is shown in Figures B-4.12 (a), (c) and (d).

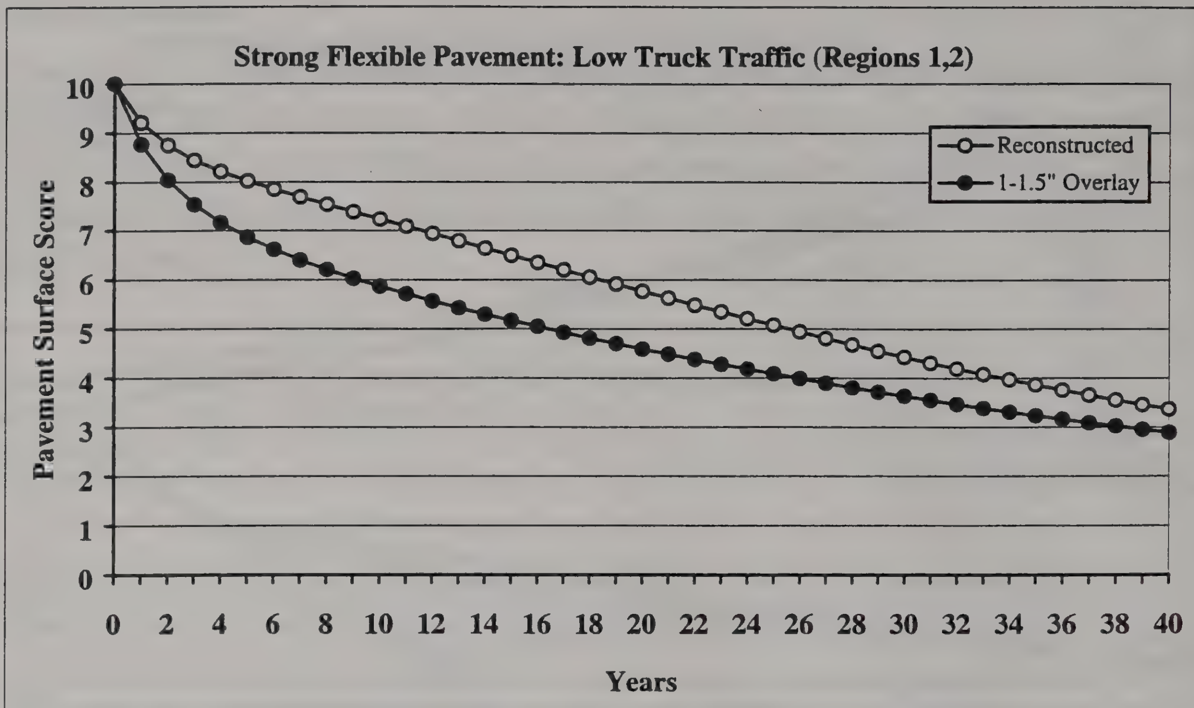

Figure B- 4.12 (a) Effect of Treatment on Flexible Pavement Performance - Regions 1 & 2

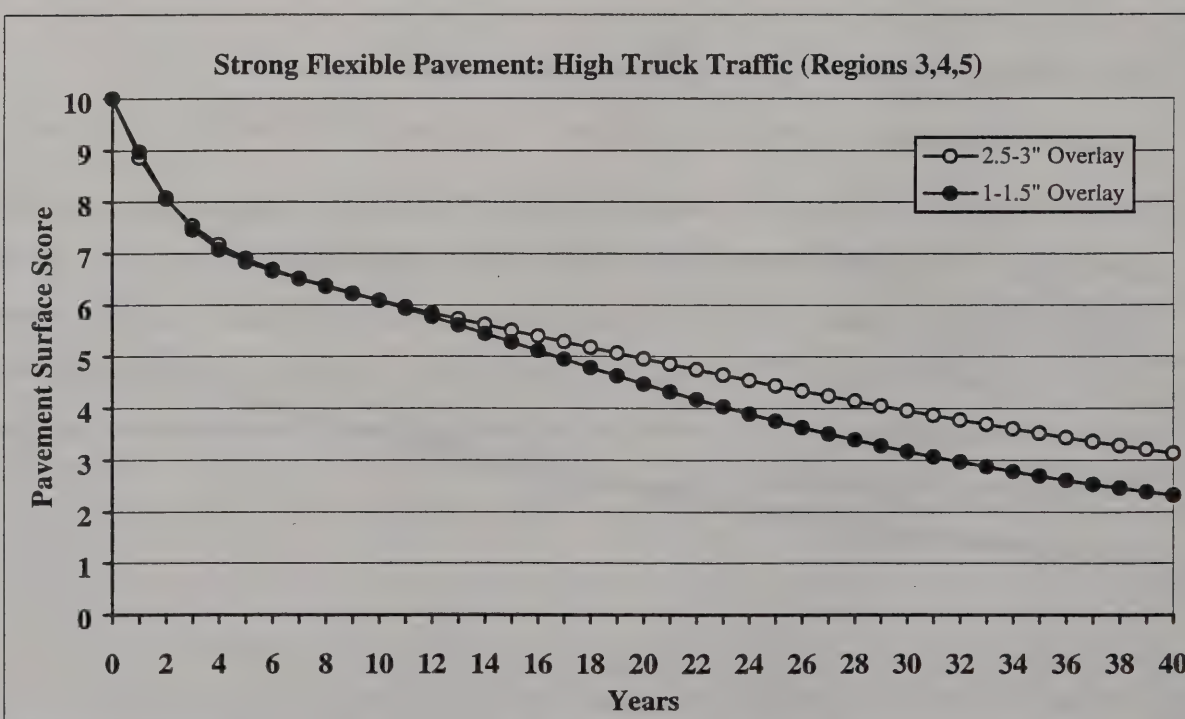

Figure B- 4.12 (b) Effect of Treatment on Flexible Pavement Performance - Regions 3, 4, & 5

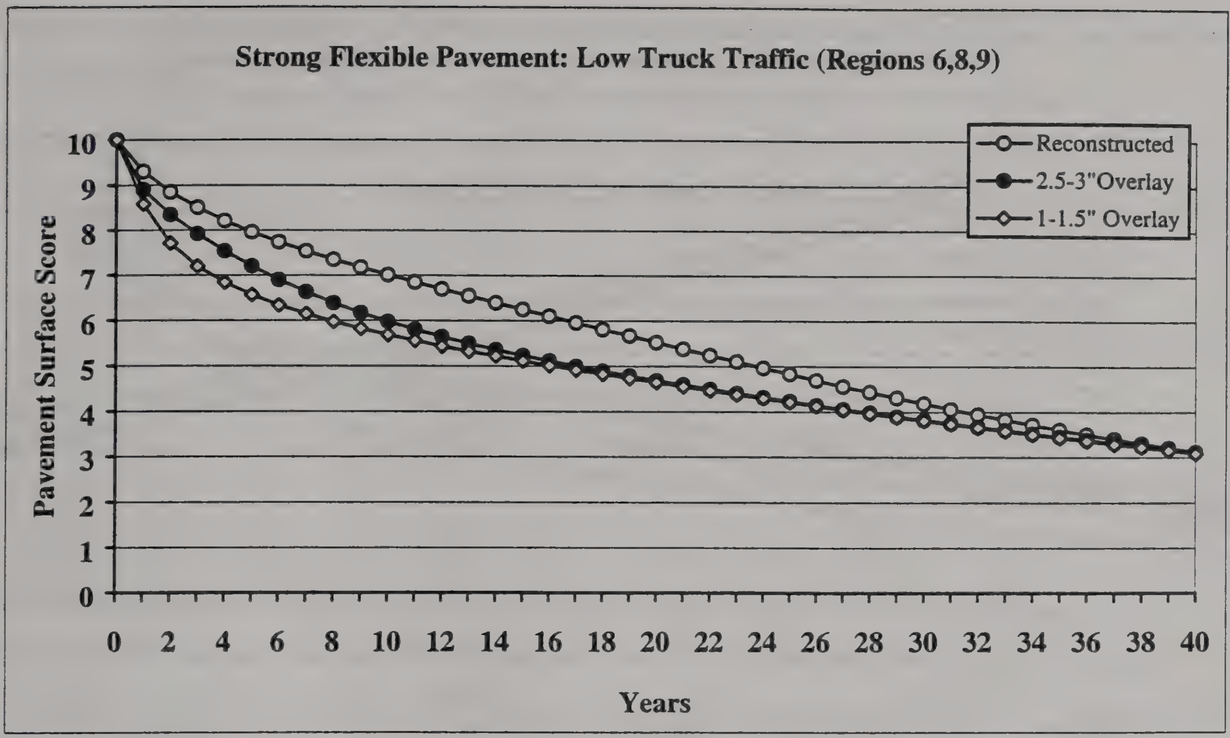

Figure B- 4.12 (c) Effect of Treatment on Flexible Pavement Performance - Regions 6, 8, & 9

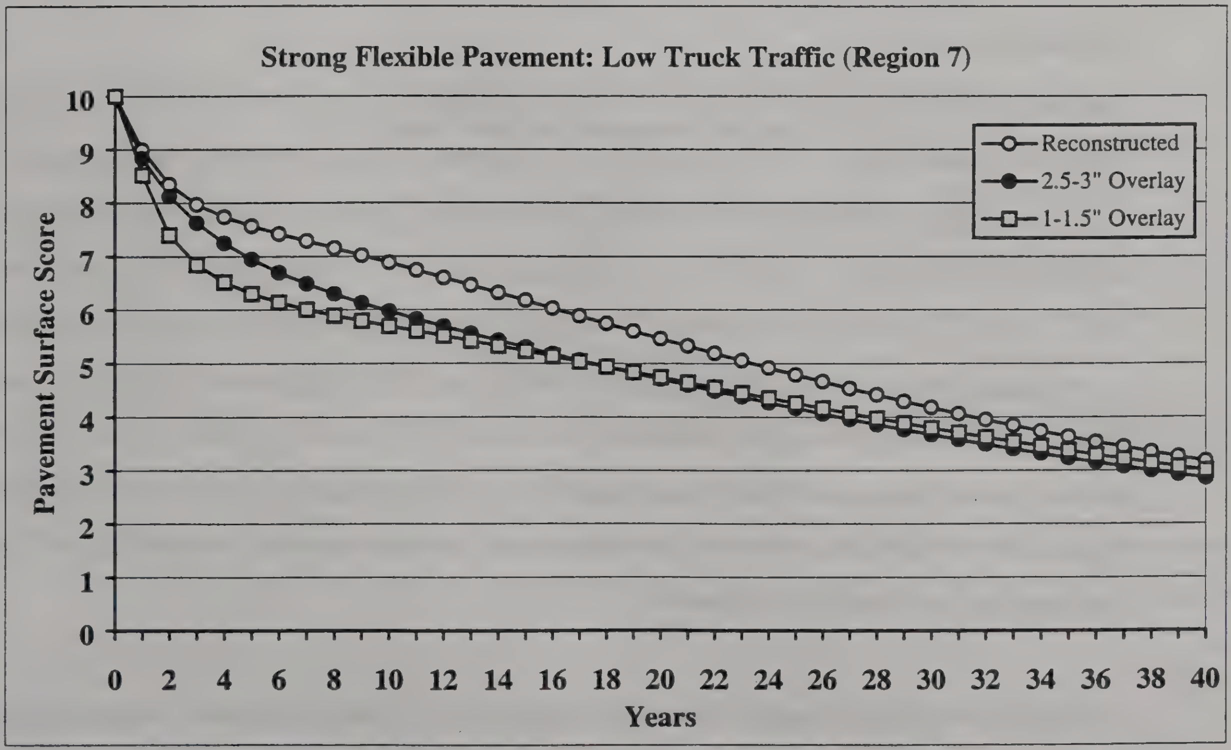

Figure B- 4.12 (d) Effect of Treatment on Flexible Pavement Performance - Region 7

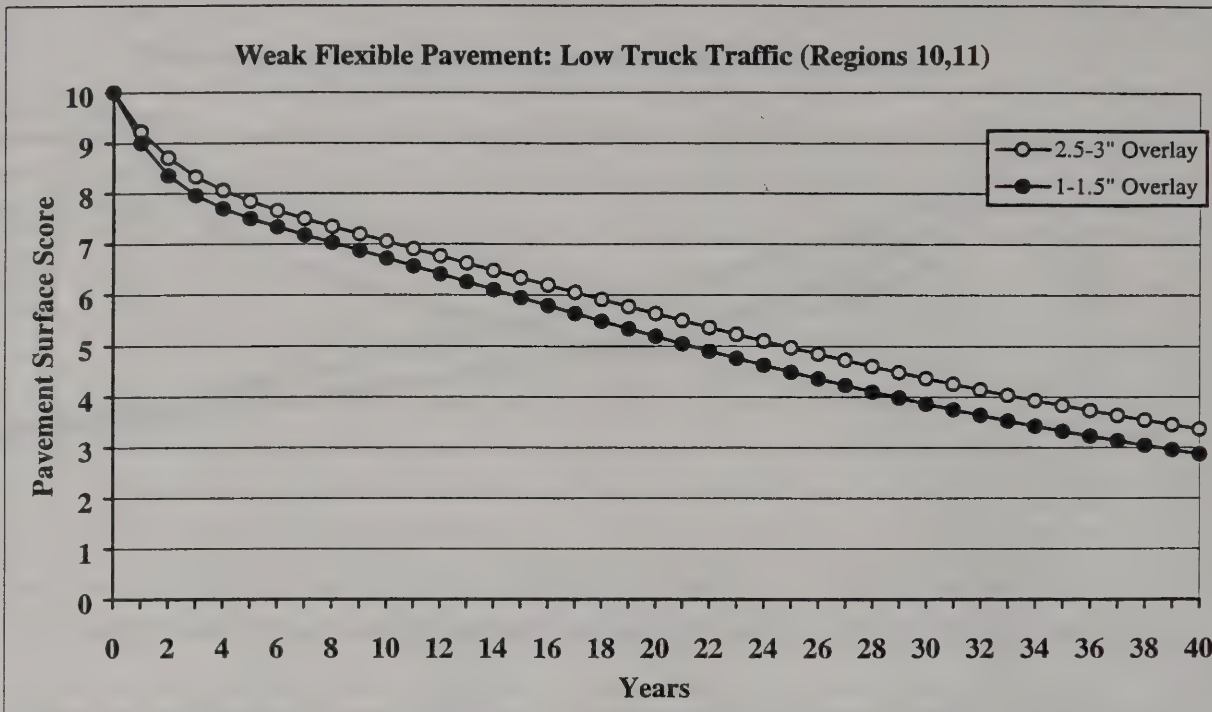

Figure B- 4.12 (e) Effect of Treatment on Flexible Pavement Performance - Regions 10 & 11

Overlaid Pavements

One would expect to see that the more structural-intensive treatments perform better than the least structural-intensive. This tendency was observed in the case of flexible pavements. In the case of overlaid pavements this tendency is observed in some cases but is not consistent across all cases. For example, Figure B- 4.13 (a) shows that 4-6" overlaid pavements performed worse than 1.5" and 3" overlaid pavements. This result can be explained by the fact that deterioration of overlaid pavements is a reflection of the underlying (old) rigid pavement layers. This means that if a badly distressed rigid pavement is overlaid with A 4-6" overlay, it is likely to show distress earlier than a moderately distressed rigid pavement that is overlaid with a 2.5" overlay. Figures B-4.13 (b) to (e) present other examples of the effect of treatment on the performance of overlaid pavements in other regions.

All these results are indicators that the performance of overlaid pavements vary greatly even for those that are supposed to be in performance-homogeneous categories. There may be a need to standardize surface preparation of distressed rigid pavements prior to overlaying, if one is to see

consistent performance trends. However, the distress models estimated here are still valuable for use in the PMS.

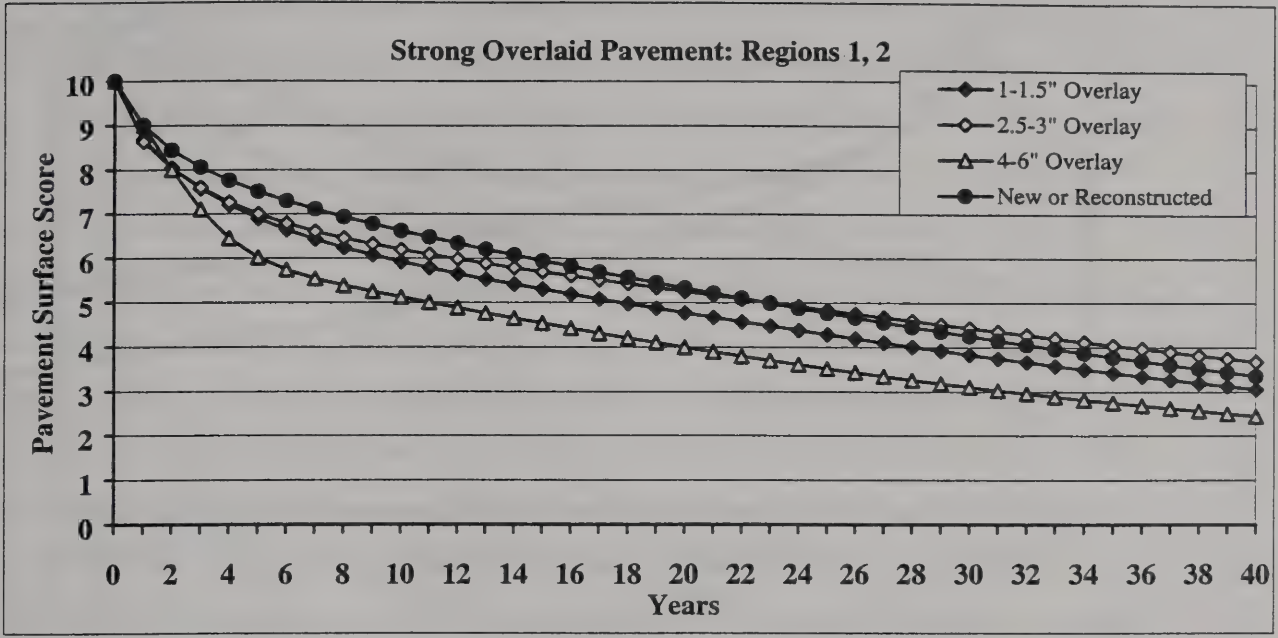

Figure B- 4.13 (a) Effect of Treatment on Overlaid Pavement Performance - Regions 1 & 2

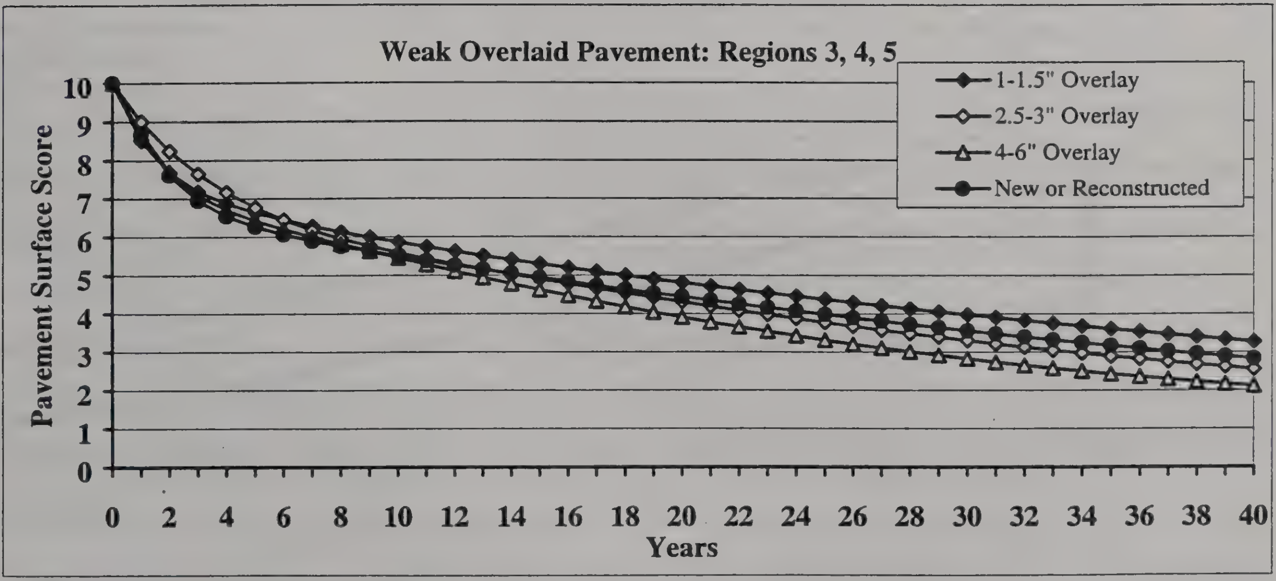

Figure B- 4.13 (b) Effect of Treatment on Overlaid Pavement Performance - Regions 3, 4, & 5

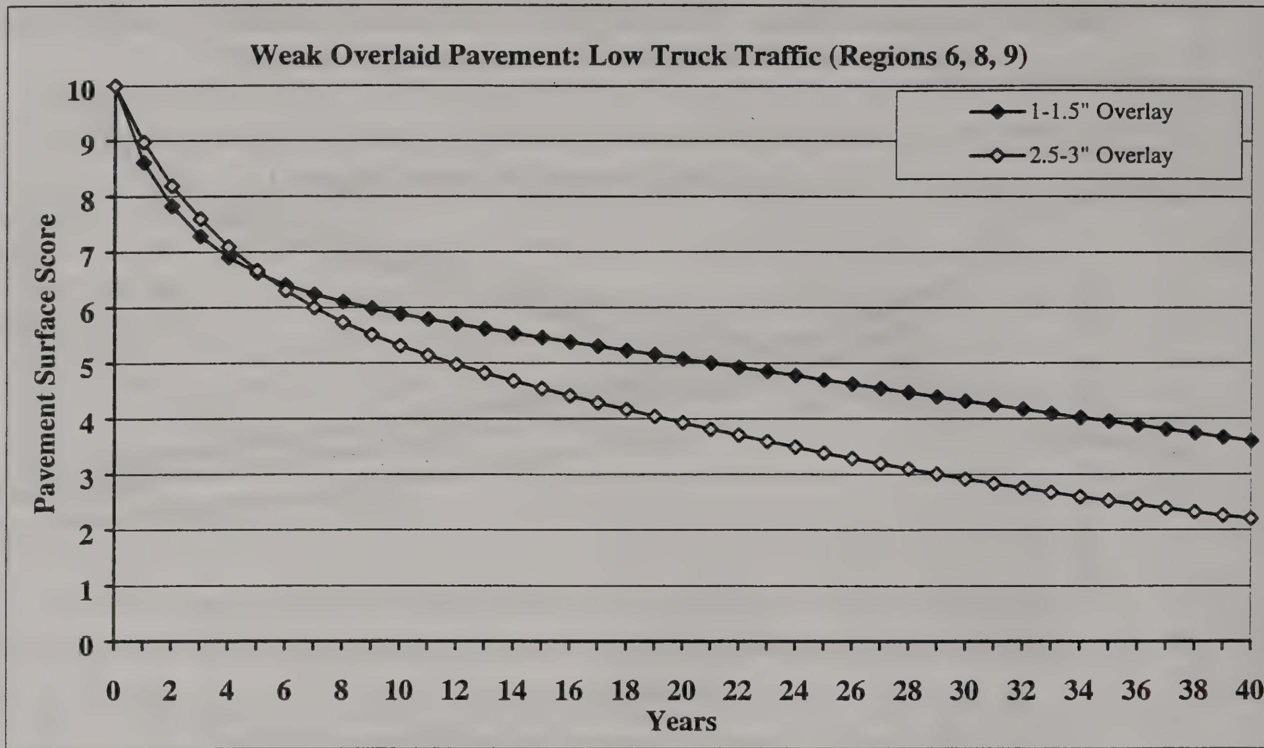

Figure B- 4.13 (c) Effect of Treatment on Overlaid Pavement Performance - Regions 6, 8, & 9

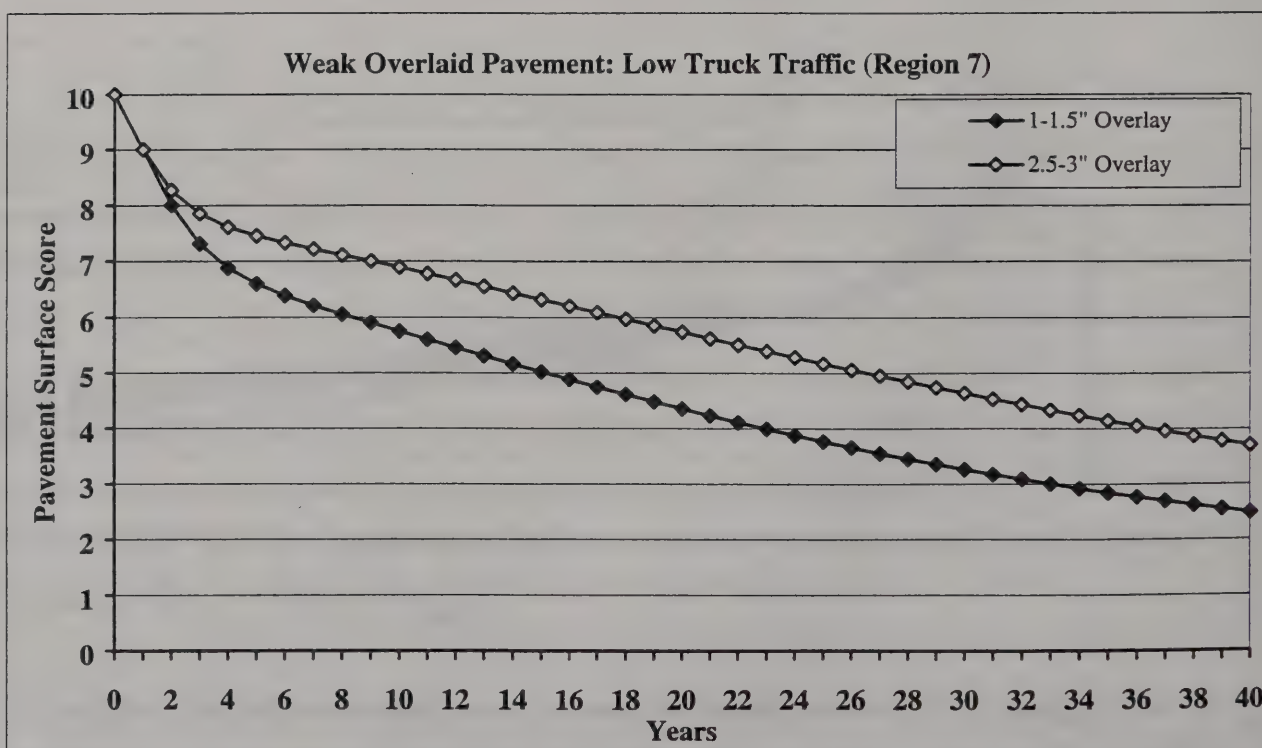

Figure B- 4.13 (d) Effect of Treatment on Overlaid Pavement Performance - Region 7

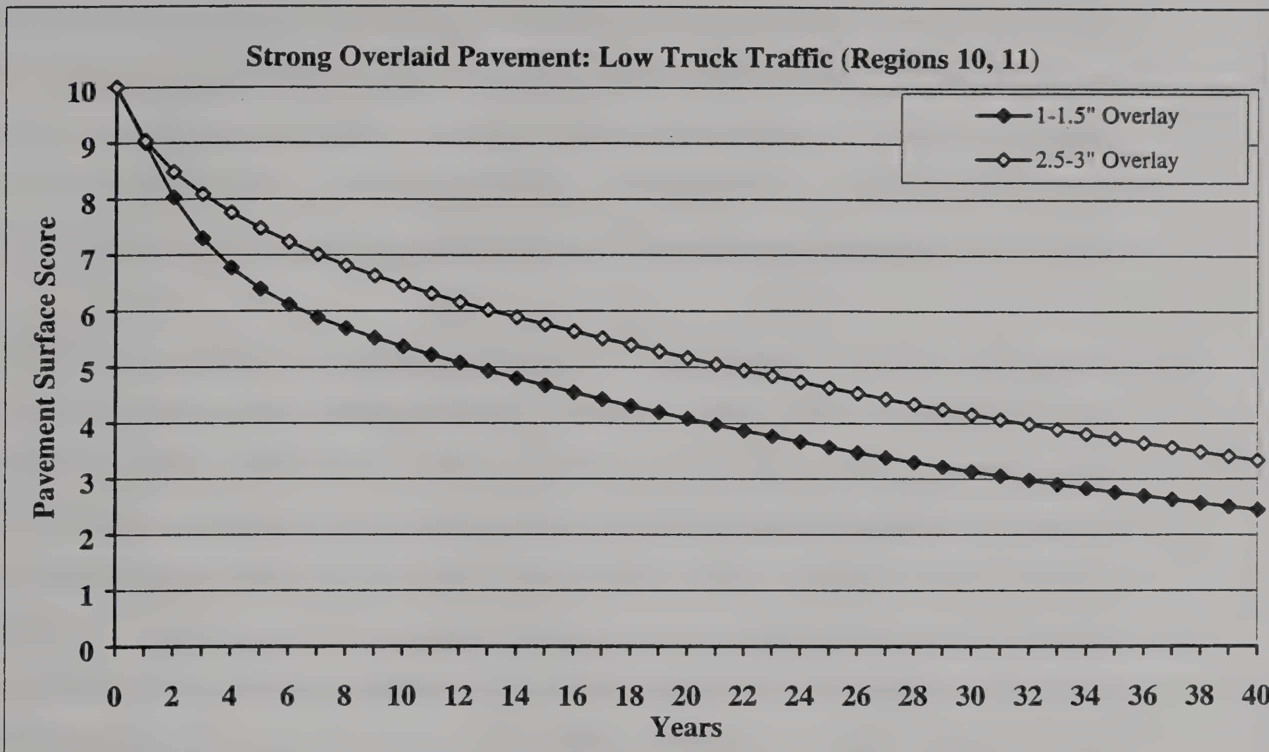

Figure B- 4.13 (e) Effect of Treatment on Overlaid Pavement Performance - Regions 10 & 11

4.5 SUMMARY

This chapter presented results of the estimation of pavement distress models or performance models. Pavements were grouped into performance-homogeneous categories and separate models were estimated for each category. These models were estimated as Markov transition probabilities using a formulation given by Equation 3.4. An example of these probabilities is shown in Table B- 4.6. All transition probability matrices are presented in Appendices F-1 to F-3. For purposes of determining the effects of the various factors used to categorize pavements, average performance curves were used. These curves were estimated using Equation 3.3 in Chapter 3.

In general, it was found that all factors used to categorize pavements had some influence in the performance of pavements. These factors include (a) pavement geographic location which was related to the 11 NYSDOT regions, (b) pavement type, i.e., flexible, rigid or overlaid, (c)

pavement strength, based on pavement layer types, (d) traffic loading, based on the volume of truck traffic, and (e) treatment type. The results show that most pavement categories registered significant variation in performance among pavement types and geographical location. In general, rigid pavement performed better than either flexible or overlaid pavements. On the other hand, flexible pavements showed better performance compared to overlaid pavements.

In comparing regions, it was generally observed that pavements in regions 1 and 2 performed better than those in other regions. However, this observation was not always the case where overlaid pavements were concerned. In fact, the results imply that the performance of overlaid pavements is more erratic than the performance of either rigid or flexible pavements. This may be attributed to the fact that the underlying layers (old distressed rigid pavements) of overlaid pavements have more variability even among pavements in the same category or region. Since overlaid pavements make the bulk (about 53%) of pavements under NYSDOT, there is a need to look into a standardized approach of rehabilitation so as to get more consistent performance.

The other factors used to categorize pavements (strength, truck traffic and treatment type) also showed some effect on performance, even though not in all categories. In summary, therefore, we would recommend all five factors to be used in future distress performance models. The transition probabilities presented in Appendices F-1 to F-3 will be used in the PMS model presented in Task-1 Report[5]. These probabilities will need updating from time to time by taking advantage of newly collected data. This updating process will also be able to capture any deviation in performance characteristics as time goes by. We would recommend that the probabilities be updated once every five years.

REFERENCES

PART C

C. Evaluation and Recommendations on NYSDOT Pavement Work-History Record Keeping from LCC Perspective

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1. INTRODUCTION

IMPORTANCE OF WORK HISTORY IN PAVEMENT MANAGEMENT

In this report, NYSDOT work-history record keeping is discussed. The importance of work-history record keeping for pavement management cannot be over emphasized. The main driver of a pavement decision support system is the set of pavement performance models for the different categories of pavements. As elaborated Part B, the performance of highway pavements depend on its treatment history. If we are to group highway pavements into performance-homogeneous categories for efficient application of management decision tools (see Part A), these categories ought to consist of pavements of similar traffic levels, pavement types and work-history types. Such categories will benefit from joint performance models and realistic pavement management strategies. In keeping records of work-history, it is not sufficient to know what was last done on a pavement segment but rather what has been done on it since its construction. This report will examine what kind of records NYSDOT keeps and what can be done to improve work-history record keeping.

2. NYSDOT HIGHWAY-RELATED RECORD KEEPING

NYSDOT keeps record of numerous aspects of its highway system. These records include:

(i) highway identification and location information

(ii) highway physical characteristics

(iii) traffic information

(iv) pavement condition information.

All records are based on pre-designated highway segments. There are about 22,000 highway segments covering about 37,000 lane-miles (or about 15,000 centerline-miles) of the state highway system. Sections 2.1 to 2.4 show the kind of information kept in the four record types listed above.

2.1 Highway Identification & Location

These records identify highway segment by type and location. These records are well defined elsewhere.[1] This information includes:

- Route Number
- Region and County Name
- County Order Number
- Control Segment Number
- Starting Milepoint
- Ending Milepoint
- Reference Marker
- State Highway Number
- Residency Code

Other records related to highway identification and location include:

- Terrain Type
- Area Type
- Culture
- Functional Classification
- Highway Control Code
- Access Code
- National Highway System Code
- Route Overlap Status

All this information is very useful in locating highway segments and categorizing them into specific jurisdictions and functional classifications.

2.2 Highway Physical Characteristics

In addition to traffic and work-history data, physical characteristics information is useful in categorizing pavements into performance homogeneous groups. The following is a list of records currently maintained by NYSDOT regarding the physical characteristics of highway segments.

- Section Length
- Number Of Roadways
- Number Of Lanes
- Median Type
- Median Width
- Pavement Type (rigid, overlaid, or flexible)
- Pavement Width
- Pavement Surface Type
- Pavement Base Type
- Pavement Sub-Base Type
- Shoulder Type
- Shoulder Width

2.3 Traffic Information

This information is also useful in categorizing pavements into performance categories, as well as determining user cost associated with pavement segments. Information currently collected include:

- Passing Sight Distance
- Percent Parking
- AADT Volume (vehicles per day)
- Traffic Count Year
- Design Hourly Volume
- Adjusted Rated Capacity
- Volume/Capacity Ratio

Percent Trucks

Percent Tandem Trucks

Truck Classification Year

2.4 Pavement Condition Information

The last set of records kept by NYSDOT related to highway pavements relate to pavement condition. These records include the historical distress (surface scores) data from 1981 to current date, current dominant distresses, and information about latest pavement treatment work done. The list below shows the type of records maintained.

1981-to Current Date Surface Score

Dominant Distress - Faulting

Dominant Distress - Spalling Isolated

Dominant Distress - Spalling General

Dominant Distress - Alligator Cracking Isolated

Dominant Distress - Alligator Cracking General

Dominant Distress - Widening Drop Off

Year of Latest Work

Work Type

The historical record keeping of distress data (1981 to date) has been very useful in developing pavement performance models (see Task-2 Report[2]). This kind of record keeping should continue for future use in updating the performance models. The information about dominant distresses is also very valuable, especially in deciding about specific treatment types. The record that need improvements so as to enhance the performance prediction models as well as treatment selection strategies is the work-history. Currently, only the latest work type and year is recorded. This information alone is not enough to explain the variation in distress scores that are recorded annually. The following section discusses what improvements can be done in the

recording of pavement work history for efficient use in pavement management. Most of these improvements do not necessarily imply collecting new data but rather keeping currently collected data in a more useful format.

3. Proposed Work-History Record Keeping

In Section 2.4, it was shown that the work-history data recorded include **Year of Last or Latest Work, and Work Type**. Year of latest work is the year when the latest resurfacing or reconstruction work was performed on the highway section by contract or state forces. Work type shows codes that are consistent with treatment types used by NYSDOT. These codes include:

Code	Work Type
1	Single-course asphalt concrete overlay 1" - 1.5"
2	Two-course asphalt concrete overlay 2.5" - 3"
3	Three-course asphalt concrete overlay 4" - 6"
4	In-place recycling, surface course only
5	In-place recycling, full depth
6	Reconstruction total pavement replacement
7	Other. Treatments used for special purposes.

There are two aspects of the work records that can be enhanced. A minor improvement has to do with the coding of work type, and a major improvement involves the frequency with which this information is to be kept.

3.1 Record Frequency

Currently, the past work records show only the latest treatment work and the year it was done. Such information hides valuable insights that can be derived from the

variability of the annually kept distress data. Pavement performance characteristics have a lot to do with work history which can be misinterpreted if work history records are insufficient or unreliable. Annual records of pavement treatment are very important for modeling of pavement performance and for future updating of performance model. As discussed in Section 3.2, all types of pavement treatment records, including do-nothing should be maintained annually, similar to pavement distress data.

It is our expectation that this exercise will not impose any additional effort on regional offices since such information is readily available. If records for previous years can be reliably extracted, that information can also be used to refine current pavement performance models.

3.2 Work-Type Record Improvement

Records of previous work type should include do-nothing, as well as preventive maintenance. This information is important because there is a correlation between pavement performance, as measured by distress indicators, and the frequency of preventive maintenance. Current records do not show whether no treatment or preventive maintenance was done on a pavement section. Since preventive maintenance cost money but sometimes can be very cost-effective, it is important to determine its effect on the propagation of pavement distress. Therefore, it is proposed that the current seven work-type categories be increased to nine to include two categories of **Do-Nothing** and **Preventive-Maintenance**. Alternatively, to be consistent with INAM treatment strategies,[4] one can use the codes for the eight treatment strategies shown in Table C- 3.1, including a ninth category for special treatments such as rehabilitation of bridge deck, etc.

3.3 SUMMARY

In summary, pavement treatment work records are important in pavement management because of their role in pavement performance modeling and model updating. Such records should include annual work types done on each pavement section. Therefore, there will be one work-type record for each pavement section each year, similar to the pavement distress data. The work-type data should include not only resurfacing and reconstruction work but even preventive maintenance and do-nothing. These records can be kept in the same format as the rest of the S-1 data, such as surface scores, and stored in the mainframe computer. However, the database architecture may need to be modified to allow on-line accessibility, through pcs and workstations, by frequent users of this information if this is currently not possible.

Table 3.1 Description of Repair Actions *(a)* Related to the Three Pavement Types.

Code / Repair Action / Pavement Type	1 Do Nothing	2 Preventive Maintenance	3 Preventive Maintenance (High Cost)	4 Corrective Maintenance (Rigid) Preventive Maintenance-Paving (Flexible & Overlaid)	5 Corrective Maintenance (High Cost)	6 Rehabilitation	7 Rehabilitation (High Cost)	8 Major Rehabilitation/ Reconstruction
RIGID	Do Nothing	Clean, Seal, Fill Joints/Cracks	Clean, Seal, Fill Joints/Cracks Prepare & Repair Spalls	Clean, Seal, Fill Joints/Cracks Prepare & Repair Spalls, Partial Slab Grinding/ Texturing		4" ACC Overlay 3" ACC Shoulders	5" ACC overlay 3" ACC Shoulders	9" PCC Paving 3" Rigid Shoulders
						All of Corrective Maintenance + Excavation, Tack Coat, True & Level, Type 3 Binder, Type 6F Top, Saw & Seal Overlay, Drainage, Curbing, Guide Rail, Signage, Landscape, Stripping.	All of Corrective Maintenance + Excavation, Tack Coat, True & Level, Type 3 Binder, Type 6F Top, Saw & Seal Overlay, Drainage, Curbing, Guide Rail, Signage, Landscape, Stripping.	Pavement Removal, Excavation, Subbase Items, Class C Reinforced PCCP, Drainage, Curbing, Guide Rail, Signage, Landscape, Stripping.
OVERLAID	Do Nothing	Clean, Seal, Fill Joints/Cracks	Clean, Seal, Fill Joints/Cracks Type 6F Top	1.5" ACC Armor Coat & 1.5" ACC Shoulders	1.5" ACC Armor Coat, &1.5" ACC Shoulders	2.5" ACC Overlay, & 2.5" Shoulders	4" ACC Overlay, & 3" Shoulders	Rubblize Existing Pavement, 6" Overlay, & 3" shlds
				Clean, Seal, Fill Joints/Cracks Excavation, Clean Pavement, True & Level, Type 6F Top	Clean, Seal Fill Joints/Cracks Excavation, Cold Milling, Clean Pavement, Type 6F Top	Excavation, Clean Pavement, True & Level, Type 3 Binder, Type 6F Top, Drainage, Guide Rail, Curbing, Landscaping, Signage, Stripping	Excavation, Clean Pavement, True & Level, Type 3 Binder, Type 6F Top, Drainage, Guide Rail, Curbing, Landscaping, Signage, Stripping	Type 3 Binder, Type 6F Top, Drainage, Guide Rail, Curbing, Landscaping, Signage, Stripping
FLEXIBLE	Do Nothing	Same as for Overlaid Pavements Above	Same as for Overlaid Pavements Above	Same as for Overlaid Pavements Above	Same as for Overlaid Pavements Above	Same as for Overlaid Pavements Above	Same as for Overlaid Pavements Above	10.5" ACCP, 3" Shoulders,
								Excavate, Remove Pavement, Type 1 Base, Type 3 Binder, Type 6F Top, Roadside Work as for Overlaid Pavements Above

Source: 1994 INAM Users Manual [4]

4. Pavement Roughness (Additional Record Keeping)

So far this report has discussed some of the pavement management records kept by NYSDOT and proposed work history record keeping improvements. In addition to these recommendations, it is also proposed that NYSDOT maintains pavement roughness data for the applicable sections in the same level of details as pavement distress data. Pavement roughness data is important because it is more related to user cost (vehicle-operating cost) than distress data. A pavement management system that takes into consideration user cost needs information about pavement roughness. It is understood that this data is collected biennially and on selected sections only. However, if roughness data were kept in the same data format as surface distress, then roughness performance models could be developed that would enhance decision making.

5. Conclusions

The purpose of this report is to evaluate and propose improvements to the Department's work-history record keeping. Based on the current information maintained by NYSDOT, it is evident that all the necessary information is available to have a meaningful work history database. However, at the moment this information is presented for the last work type and year it was done. Also, only resurfacing or reconstruction work types are specifically reported. The report recommends that pavement treatment (work) information be maintained and presented on an annual basis, and that all work types, including do-nothing be encoded. This information can be kept in the same data format as pavement distress data. However, it may be beneficial if the database structure is modified to allow on-line accessibility of the frequent users.

Finally, a comment is made about the need to keep the pavement roughness data, currently collected by NYSDOT in the same level of detail and format as the distress data. This information will enhance the decision support system, especially if user costs are to be considered in that process.

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PART D

D. Evaluation and Recommendations on NYSDOT's capability to estimate Pavement Maintenance and Capital Costs

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1. INTRODUCTION

The following is a review and evaluation of NYSDOT's current capabilities to estimate pavement treatment costs and costs of maintaining and protecting traffic. This review is followed by recommendations on how to improve the existing practice. In this report, the focus will be on evaluating cost estimating capabilities from the network-level pavement management point of view.

2. EXISTING NYSDOT TREATMENT COST ESTIMATION PROCEDURES

Currently, the NYSDOT Design Quality Assurance Bureau (Albany, New York) produces an annual report which details Pavement Management Network-Level Treatment Costs. This report discusses current trends that have effects on the price and implementation of various pavement management strategies during the prior fiscal year. The report culminates in a table entitled Summary of Costs for Various Pavement Treatments, similar to the one presented in the Appendix . This table displays the regional and statewide average costs per lane-mile (in $1,000) for the various treatment strategies.

Information that is not displayed in the average cost table (see the Appendix), but of interest, is the data from which the table is derived. The average cost of each treatment is computed by summing the total of its line item costs as bid on previous regional contracts. Such information could be very useful in developing better treatment cost functions as discussed in Section 3.

The total weighted average costs presented in these tables also consider the contribution of the following factors to the total cost:

- Cost of work on pavement only.
- Cost of work on the roadside adjacent to pavement.
- Cost of work being done to improve safety.
- Cost of overhead.

Table 1: NYSDOT Treatment Strategies

STRATEGY		TREATMENT	PAVEMENT
A	Preventive Maintenance	Reseal Joints	Rigid
B	Preventive Maintenance (High Cost)	Reseal Joints, Patch Spalls	
C	Corrective Maintenance or Minor Rehabilitation	Mill Joints, Reseal Joints, Patch Spalls	
D	Major Rehabilitation	4" ACC Overlay with 3" ACC Shoulder	
E	Major Rehabilitation (High Cost)	5" ACC Overlay with 3" ACC Shoulder	
F	Reconstruction	9" PCC Reconstruction with 3" ACC Shoulder	
G	Preventive Maintenance	Fill Cracks	Flexible/ Overlaid
H	Preventive Maintenance (High Cost)	Patch Pavement, Fill Cracks	
I	Corrective Maintenance or Minor Rehabilitation	1.5" Armor Coat, 1.5" ACC Shoulder	
J	Corrective Maintenance or Minor Rehabilitation	Mill Pavement, 1.5" Armor Coat, 1.5" ACC Shoulder	
K	Major Rehabilitation	2.5" ACC Overlay with 2.5" Shoulder	
L	Major Rehabilitation (High Cost)	4" ACC Overlay with 3" ACC Shoulder	
M	Rubblize (Overlaid Pavements Only)	Remove ACCP, Rubblize PCCP, 6" ACC Overlay with 3" Shoulder	
N	Reconstruction	10.5" ACC Reconstruction with 3" ACC Shoulder	

3. Observations and Recommendations

3.1 General

Treatment cost estimates currently used by NYSDOT are appropriate for network-level planning and budgeting if the treatment strategies listed in Table 1 are triggered at same specific pavement surface conditions as those shown in Table 2. In effect, Table 1 and Table 2 together constitute a maintenance and rehabilitation (M&R) policy. For example, preventive maintenance strategies A (for rigid pavement) and G (for flexible/overlaid pavement) in Table 1 are expected to be performed when the respective pavement surface ratings have reached 8 (see to Table 2). Similarly,

reconstruction strategies F (for rigid pavement) and N (for flexible pavement) are expected to be performed when surface scores are between 1 and 3. However, if a decision support tool, such as the model proposed in Task-1 report *(1)* is desired, in order to generate optimal M&R policies, more detailed cost functions are needed. These cost functions are discussed in Section 3.2.

As pointed out earlier, the cost estimate figures such as those in the Appendix may be suitable for network-level planning and budgeting. However, they are certainly not adequate for project-level planning. The item unit cost of work is a function of the magnitude of a project. Large paving jobs tend to reduce the unit costs of component items because equipment and manpower may be more effectively utilized. Small contracts may result in a somewhat inefficient resource utilization and higher bid prices. The discussion in this report is relevant to the evaluation of cost data for network-level planning only.

3.2 Treatment Cost Functions

The cost of any pavement treatment strategy will depend on the pavement condition at which it is applied. For example, a pavement section at surface score 3 requires more preparatory work to restore the pavement to a point where it can be rehabilitated than a pavement section at surface score 5. This variability in cost as a function of surface condition is not currently reflected in the cost estimates. M&R cost estimates by pavement surface condition (at the time of treatment) will constitute cost functions. Such functions can be very helpful in developing M&R policies.

Examples of cost functions can be seen in Sharaf et al. *(3)* who compiled cost data for flexible and overlaid pavements under the management of the U. S. Construction Engineering Research Laboratory (CERL). For example, their rehabilitation cost was divided into a fixed and a variable cost. Fixed cost is the cost of applying a particular rehabilitation treatment on an already prepared surface. This cost depends only on the type of rehabilitation work. Variable cost, on the other hand, is the surface preparation

cost. This is the cost of preparing a damaged pavement surface so that it is ready for any treatment. Variable cost depends on pavement surface condition - the better the surface condition, the less the variable repair cost. The total cost is the sum of variable and fixed cost which will be a function of pavement surface condition.

Table 2 Network-Level M&R Trigger Conditions

Pavement Surface Score	Rating	Distress Frequency	Distress Severity	Treatment Categories Assigned
10	Excellent	None	None	Do Nothing
9	Excellent	None	None	Do Nothing
8	Good	Infrequent	Very slight	Preventive Maintenance
7	Good	Infrequent to Occasional	Slight	Preventive Maintenance (High Cost) Preventive Maintenance (Paving)
6	Fair	Occasional to Frequent	Slight to Moderate	Preventive Maintenance (Paving) or Corrective Maintenance (High Cost) or Rehabilitation
5	Poor	Occasional to Frequent	Moderate to Severe	Rehabilitation or Rehabilitation (High Cost)
4	Poor	Frequent	Severe	Rehabilitation (High Cost) or Major Rehabilitation
1 - 3	Poor	Very Frequent	Very Severe	Major Rehab. / Recontruction

Source: The NYSDOT Pavement Condition for New York's Highways: 1994 (2)

The Study Team proposes the development of M&R cost functions to be used in place of the current average cost estimates. It is anticipated that this process will not involve

any new data collection efforts on the part of NYSDOT, except that the current data be available in more details. The cost functions will merely be extensions of the current average costs. Instead of an average line item unit cost, this unit cost will be a function of the existing pavement surface condition. The determination of cost functions will evolve over time as annual project cost data include the necessary information for this purpose, namely the average pavement condition and the corresponding line item cost for each project. However, the decision support model proposed in Task-1 Report will be implemented using the current average costs. This means the model will assume that line item costs will only vary with region, and not with pavement condition. As more information is made available the current average costs will be replaced by these cost functions.

3.3 Maintenance and Protection of Traffic

Currently, the line item for maintenance and protection of traffic in NYSDOT contracts is bid in terms of lump sum. (The Department has additional line items for construction signs, message boards, pavement markings, delineation, and other temporary traffic flow devices). NYSDOT also has established standards and specifications for establishing traffic protection for both stationary and mobile work zones. For estimation purposes, NYSDOT engineers usually estimate traffic maintenance cost as a percentage of the contract cost and the complexity of the construction staging.

Upon examination of the pavement treatment strategies, various traffic maintenance strategies are required. For high cost treatments, long term lane or road closures will be required for safe work sites. For lower preventive maintenance, mobile work zones are more common. Since the required maintenance and protection of traffic is so diverse, perhaps the lump sum bid is the best alternative. Similar to the current method of estimating treatment costs, the Department may establish the corresponding traffic maintenance costs for each treatment as a percentage of the project cost.

Obviously, maintenance and protection of traffic is not a function of the pavement condition at the time of treatment. Consequently, the cost functions proposed in Section 3.2 will still be valid and only a fixed cost (depending on the type of treatment) will be added to each function to reflect the cost of protection and maintenance of traffic.

4 SUMMARY

In summary, the Study Team thinks that the Department capability in estimating pavement maintenance and capital cost is good. For the purpose for which it was intended, the cost estimates are quite adequate for network-level planning. The current cost estimate data are detailed enough to enable the user to incorporate regional variation. However, in view of the decision support enhancements being proposed by the Study Team, the current cost estimates will need to be enhanced. Instead of reporting maintenance and capital cost estimates as average cost per treatment strategy, it would be better if these costs could be distinguished by the average pavement surface condition at the time of treatment. This way the resulting cost estimates or functions will be sensitive to both regional variation as well as pavement condition variation. Such functions will greatly enhance the M&R policies resulting from the proposed pavement management models.

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3. Sharaf, E.; E. Reichelt; M. Y. Shahin; K. C. Sinha, "Development of a Methodology to Estimate Pavement Maintenance and Repair Costs for Different Ranges of Pavement Condition Index," Transportation Research Record 1123, pp. 30-39, Transportation Research Board, National Research Council, Washington D C, 1987.

APPENDIX

1994 (August) NYSDOT Average Treatment Costs (Including Expanding factors)

PART E

E. Evaluation and Recommendations on NYSDOT Road User Costs for Network-Level LCC Analysis

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1. INTRODUCTION

This is the fifth task in the Scope of Services which states that:

The consultant shall review and evaluate the Department's capability to estimate the road user delay cost for pavement repair strategies and compare it with that of other agencies. Recommendations for improvements shall be made, including when and how to include user delay costs in LCC analysis. The Department will review and concur with the recommendations in draft. The consultant shall incorporate any revisions required by the Department in the final recommendations.

The following report is a review and evaluation of NYSDOT's current capability to estimate both road user time-delay-costs and road user vehicle-operating-costs, as well as recommendations on how to improve upon the Department's existing practice. In this review a distinction is made between road user delay costs during construction and maintenance activities, and road user vehicle operating costs escalation due to pavement deterioration as measured (currently) by Pavement Surface Rating - PSR (a distress measure) and International Roughness Index - IRI (a roughness measure). Also a distinction is made between road user cost reduction due to highway capacity improvements and user cost reduction due to pavement riding quality improvements.

There has been a long debate among transportation engineers and planner whether or not to include user cost in the evaluation of pavement improvement projects. As pointed out in the HUCA manual,[1] NYSDOT is in a position of trust with the people of New York State and is obligated to steward the State's facilities and resources in a prudent manner. Furthermore, there are more pavement improvement needs than there is available funding. Therefore, NYSDOT is obligated to spend community resources on projects that give the public the greatest benefit from its investment. Consequently, the cost borne by the user of a road facility ought to be taken into consideration in project or program selection.

In order to understand when and where road user cost ought to be considered, it is important to distinguish the various components of this cost. Road user cost includes all cost incurred by the user of the highway facility as a consequence of using that facility. This cost is comprised of vehicle operating cost - VOC (which includes fuel cost, oil & tire cost, ownership cost, vehicle maintenance cost, and administrative cost - mainly for commercial vehicles), delay cost, and accident cost. In analyzing road improvement projects, the reduction in these user costs can be

very significant and ought to be used as benefits for the projects. However, not all types of user costs need to be considered when analyzing specific improvement projects. For example, in a capacity improvement project (such as widening lanes or adding more lanes to a section of highway) intended to reduce congestion, all three types of user cost (i.e., VOC, delay cost, and accident cost) can potentially be reduced and should be included in the analysis. However, in a surface quality improvement project, such as resurfacing, where the main objective is to improve riding quality, VOC is the major cost component affected. It is also possible that accident cost may be reduced if the resurfacing was done to improve safety factors such as surface skid resistance. Time delay cost become a factor in a surface improvement project only if the pavement had deteriorated to such a low surface quality as to affect running speeds. If pavements are maintained such that their surface quality is above a threshold (say PSR $\geq$ 5), then speeds will not be adversely affected by surface quality. In such cases, VOC becomes the main component of road user cost. Models estimating user cost that is sensitive to pavement surface quality will be the focus of this report.

The following section discusses current NYSDOT practice in estimating road user costs.

2. EXISTING USER COST ESTIMATION PROCEDURES BY NYSDOT

NYSDOT has two methods of estimating user costs. The first method is based on a spreadsheet program called Highway User Cost Accounting (HUCA) model which is good for capacity improvement projects. This method is discussed in Section 2.1. The second method is based on approximate figures of estimating VOC, based on the pavement distress condition (PSR). This method is discussed in Section 2.3.

2.1 NYSDOT'S HIGHWAY USER COST ACCOUNTING (HUCA)

Overview

NYSDOT's HUCA is a microcomputer (based on LOTUS 1-2-3 spreadsheet) model that can be used to estimate the impact of highway capacity improvement to user cost (VOC, delay cost and accident cost). The model can accept user inputs and in the absence of user inputs, default values

are used. The main purpose of the program is to compute project benefits as a result of capacity improvements.

Use of HUCA in the Economic Analysis of Capacity Improvement Projects

Given a capacity improvement project, project cost, project life, inflation and discount rates, HUCA can be used to estimate life-cycle reductions in vehicle operating cost, user delay cost (both cost reductions are due to expected increase of vehicle running speeds) and user accident cost. These user cost reductions can then be considered as benefits to the project and further benefit/cost analysis can be performed to facilitate project selection and resource allocation. HUCA does this analysis for various types of facilities such as freeways, arterials, two-lane/multi-lane rural highways, and signalized intersections. Other types of analyses that HUCA can perform include the impact of lane closure on user cost, the user benefits of nighttime construction under congested flow conditions, and the comparison of user benefits of on-site vs. off-site detours during construction.

Shortcomings of HUCA

Pavement Surface Quality Improvement

As pointed out, HUCA is intended to be used to analyze the impact of highway capacity improvement on user cost. In its present state it cannot estimate user cost due to pavement surface quality improvement, which is the main type of work done in the pavement maintenance management program. Section 2.2 discusses how NYSDOT estimates user cost benefits due to surface quality improvement.

Unaccounted Impact of Capacity Improvement

Currently, HUCA does not take into account the impact of capacity improvement on users' route choice. Not every capacity improvement project will result in delay or congestion reduction. In order to determine the consequence of capacity improvement on the flow of traffic, a careful evaluation of users' choice of routes is warranted. This type of analysis is known as NETWORK DESIGN ANALYSIS (see Abdulaal & LeBlanc[2], or Poorzahedy & Turnquist[3]). This type of analysis is especially necessary if the section to be improved is part of a network of highways

which offer users alternative routes. Without such analysis one cannot be sure by how much congestion will be reduced as a result of capacity increase. In fact, some capacity improvement projects can result in an increase in congestion in the network (This phenomenon is also known as the Braess Paradox - see Pas & Principio[4]). HUCA is a very valuable model, especially if it used to analyze isolated sections of highway. However, care must be taken when used to analyze capacity improvements in section of a congested urban network.

2.2 NYSDOT'S ROAD USER COST RELATED TO PAVEMENT SURFACE QUALITY

Presently, NYSDOT attempts to quantify road costs as part of a yearly study, Pavement Condition of New York's Highways[5]. This study attempts to describe overall condition of the State's paved highway network. The Department uses a qualitative measure, the Pavement Surface Rating Scale (PSR), to assign a rating to each section of pavement under the State's jurisdiction. NYSDOT utilizes specially trained personnel to rate each pavement (annually) using a windshield survey method. The actual rating (PSR) is a function of the visible severity and extent of primary distress of the pavement surface.

Based on the rated surface condition, the Department computes the road user costs which would be saved if the pavements were improved to excellent condition, as shown in Table 13 of the Pavement Condition of New York's Highways: 1994[5]. The Department uses the following relationships to compute the road user costs:

PSR	Excess Operating Costs (¢/mile)
1 to 5	3.5
6	1.6
7 to 8	0.6
9 to 10	0.0

These relationships proposed by Irwin[6], are rough estimates of road user costs calibrated for New York State based on World Bank relationships. It appears as if NYSDOT utilizes this data and the rest of the data in the annual Pavement Condition report as a basis for network-level assessment.

VOC is more related to pavement roughness than to pavement surface distress. Since PSR is a measure of pavement distress, it is appropriate that NYSDOT relates its VOC estimation to the roughness data until such time when the PSR scale can be correlated meaningfully to the IRI (roughness) scale. Since NYSDOT collects roughness data on a large part of its highway network, it is appropriate to look for models that can estimate VOC based on pavement roughness. Such models exist as a result of a large-scale study conducted by the World Bank.[7]

In order to use the World Bank models, NYSDOT needs to calibrate the respective parameters to reflect New York State vehicles and highway conditions. This suggests a new study to collect all the necessary information to enable the calibration process. However, since such a study will take a long time and is outside the scope of the present project, the next best thing to do is to borrow from models that were calibrated in areas with characteristics similar to those in New York State.

Section 3 gives a brief description of the World Bank models and Section 4 describes VOC models that may be suitable for NYSDOT. This section also recommends specific VOC (1997) figures that can be used by NYSDOT.

3. THE WORLD BANK VEHICLE OPERATING COST (VOC) MODELS

The World Bank has made a large effort in developing models that can predict road construction cost, road maintenance cost and road user cost. These costs constitute total transport cost over the lifetime of roads. In order to develop quantitative models for estimating these costs, in 1969 the World Bank initiated a study which later became a large-scale collaborative program involving road agencies and research institutions from many countries in the world. The resulting models are contained in the 1985 Highway Design and Maintenance Model (HDM3)[7] which is currently in use by many road agencies in the world. An improved and more user-friendly HDM4 is in the testing stages. One of the modules in the HDM3 estimates vehicle operating cost (HDM3-VOC). This module is discussed in detail by the World Bank HDM3 manual[7] and by Archondo-Callao and Faiz.[8] The module contains relationships for estimating VOC as a function of vehicle type and road conditions. These relationships were developed from

studies done in Brazil, the Caribbean, India, and Kenya. These models can be used to estimate VOC in other parts of the world. However, the models need to be calibrated to account for local unit costs, vehicle and road characteristics. Such use of HDM-VOC models was implemented in Saskatchewan, Canada.[9]

Please note that the World Bank VOC models have not been validated for congested traffic conditions. They are valid for free-flow conditions.

4. NYSDOT VOC MODELS

The models presented here are derived from the HDM3-VOC models. Most of the parameters have been borrowed from the models that were calibrated for the Saskatchewan[9] (Canadian) conditions. However, these calibrated parameters were further adjusted to reflect the 1997 conditions in New York State. These VOC models can be used for general use with the pavement management models developed in Task 1. These VOC models are based on pavement roughness (IRI). You may recall that the PMS models in Task 1 were based on the PSR scale. In order to bring in VOC models in the PMS models, we may need to either develop robust relationships between pavement surface rating (PSR) and roughness (IRI), or change PMS models so that they are based on pavement roughness. The following section discusses the attempt to develop relationships between PSR and IRI.

4.1 PAVEMENT CONDITION DATA

NYSDOT collects roughness data on a large portion of its highway network. This roughness data is measured in terms of the International Roughness Index - IRI (m/km or in/mi). As mentioned above, IRI data is not collected for all NYSDOT road sections. However, PSR (distress index) is collected for all road sections. Based on the 1993 IRI and PSR data collected by NYSDOT, there is a very weak relationship between pavement roughness (IRI) and pavement distress (PSR). The best relationships that could be achieved from the 1993 data is based on Equation 1. Table E- 1 shows the estimated parameters of Equation 1 for different types of pavements surfaces. These parameters are only valid for PSR values between 5 and 10.

However, it is evident that there is a very weak relationship between PSR and IRI, as indicated by the R^2 measure.

$$IRI = e^{\alpha+\beta*PSR} \qquad \ldots\ldots 1$$

where:

IRI = International Roughness Index [inches/mile]

PSR = Pavement Surface Rating (distress index between 1 & 10)

α, β = Regression parameters.

Table 1. Relationship between IRI and PSR

	Regression Parameters			
Pavement Type	α	β	R^2	Sample Size
Rigid	19.7960	-2.4665	50%	98
Overlaid	15.0507	-1.7127	33%	126
Flexible	13.2482	-1.2960	15%	1090

4.2 CALIBRATION OF VOC MODELS FOR NYSDOT

The model proposed for NYSDOT draws heavily on the Saskatchewan VOC model[9] which was calibrated from the World Bank VOC model to fit Canadian conditions. These Canadian conditions are similar to New York conditions in terms of vehicle fleet composition, highway conditions, costs of vehicle ownership, vehicle maintenance, tires, fuel and oil. Tables E-2 and E-3 show the vehicle characteristics that were either assumed or taken from the Canadian user cost survey data.[10, 11] Table E- 2 shows vehicle types that were considered in the Saskatchewan VOC calibration. It also shows the vehicle types used in the Brazilian study conducted by the World Bank. The Canadian vehicle types are similar to those seen in New York State roads. In terms of vehicle utilization, particularly for cars, it seems that the Canadian average vehicle utilization of 10,000 mi/year is on the low side, compared to the US average of 15,000 mi/year. However, differences will only be reflected in the vehicle ownership cost component of the VOC.

Table 2. Typical Vehicle Characteristics: Saskatchewan *(HDM3 Data Base)* * [9]

Vehicle Type	Curb Wt. [tons]	GVW [tons]	Maximum Rated Engine Power [hp]	Maximum Rated Engine Speed [rpm]	Annual Utilization, 10^3 [mi]	Annual Utilization, 10^3 [hrs]
Small Car: Chevrolet Chevette *(VW1300)*	1.1 *(1.1)*	-	65 *(48)*	5200 *(4600)*	10 *(12)*	-
Medium Car: Ford Granada *(Chevrolet Opala)*	1.5 *(1.3)*	-	120 *(146)*	4000 *(4400)*	10 *(12)*	-
Large Car: Pontiac Parisienne *(Dodge Dart)*	1.8 *(1.9)*	-	155 *(198)*	4000 *(4400)*	10 *(12)*	-
Utility: Ford F-Series *(VW Kombi)*	1.9 *(1.4)*	2.8 *(2.3)*	225 *(60)*	4000 *(4600)*	10 *(55)*	-
2-Axle Truck: International *(Mercedes 1113)*	6.3 *(6.0)*	16.1 *(16.5)*	166 *(147)*	2400 *(2800)*	25 *(63)*	1.2 *(2.0)*
3-Axle Truck: International *(Mercedes 1113)*	12.1 *(7.3)*	23.7 *(20.4)*	180 *(147)*	2700 *(2800)*	20 *(63)*	1.0 *(2.0)*
5-Axle Truck: Kenworth W900 *(Scania 110-39)*	16.0 *(16.2)*	41.3 *(24.3)*	350 *(285)*	2150 *(2200)*	99 *(---)*[2]	1.6 *(---)*[2]
7-Axle Truck: Western Star[2] *(---)*[1]	17.6 *(---)*[1]	59.0 *(---)*[1]	400 *(---)*[1]	2000 *(---)*[1]	99 *(---)*[1]	1.6 *(---)*[1]
3-Axle Bus: MCI *(Mercedes 0362)*	14.2 *(8.9)*	19.0 *(12.7)*	300 *(149)*	2100 *(2800)*	62 *(---)*[2]	1.6 *(2.4)*

*Note: Figures in parentheses reflect the characteristics of the fleet used in the World Bank study in Brazil

[1] Equivalents to 7-axle trucks did not exist in the Brazil study

[2] Not known

Table E- 3 is compiled from a 1986 Canadian road user survey.[11] This shows data about annual distance traveled, tire life and cost, cost of fuel, lubricants, maintenance and labor. These vehicle characteristics, especially the utilization of cars, is very similar to what can be expected in the US. Therefore, in terms of vehicle characteristics and use, there are many similarities between the Saskatchewan data and what would be expected for New York State data.

Table 3. Vehicle Fleet Data from Canadian Survey Results (*Adapted from Bein* [9])

Data Source	Vehicle Type	Annual Distance [mi]	Average Service Life Time [yr]	Average Service Life Distance [mi]	GVW [tons]	Average Tire Life [mi]	Fuel, Oil & Grease Cost [¢/mi] [1]	Tire Cost [¢/mi] [1]	Maintenance, Parts & Labor [¢/mi] [1]	Depreciation [¢/mi] [1]	Driver Wage [¢/mi] [1]
G	Subcompact	11,000	6	63,000	-	25,000	4.3	0.4	4.2	6.0	-
O	Compact	13,000	5	63,000	-	31,000	4.1	0.2	2.5	5.7	-
V	Midsize sedan	15,000	5	63,000	-	50,000	5.7	0.5	2.7	4.7	-
T	Midsize wagon	15,000	5	63,000	-	50,000	5.2	0.4	2.5	5.6	-
	Standard sedan	17,000	4	63,000	-	59,000	5.7	0.4	3.5	6.3	-
A	Standard wagon	16,000	4	63,000	-	59,000	6.4	0.5	3.1	6.0	-
G	Compact pickup	11,000	5	63,000	-	28,000	5.4	0.4	1.8	6.8	-
E	Cargo van	9,000	6	63,000	2.7 - 4.1	31,000	9.1	0.4	4.3	5.8	-
N	Passenger van	11,000	5	63,000	2.7 - 4.1	38,000	9.7	0.8	4.2	7.8	-
C	4WD pickup	13,000	5	50,000	2.7 - 4.1	25,000	10.3	1.0	5.9	7.0	-
I	2WD pickup	16,000	5	63,000	2.7 - 4.1	50,000	9.2	0.7	3.9	4.8	-
E	1-ton truck	9,000	7	63,000	4.5	25,000	14.8	1.4	8.1	9.7	-
S	2-ton truck	9,000	8	94,000	9.1	31,000	20.2	2.4	10.9	15.7	-
(a) [2]	5 & 7 axle tank	95,000	7.3 [7]	700,000 [4]	54.0 - 59.0	193,000 [6]	20.2 [3]	2.8	26.9 [5]	-	32.0
(b) [2]	4 to 8 axles	96,000	7.7 [7]	740,000 [4]	41.0 - 59.0	156,000	20.4	2.3	9.3	-	47.2

[1] Based on 1986 US$, and exchange rate of CA$1 to US$0.75

[2] (a): Data from 172 bulk commodity carriers[11]

(b): Data from 474 general merchandise carriers[11]

[3] Fuel only

[4] Estimated from annual distance data and average service life in years.

[5] Includes oil and grease

[6] An average between driving tire life and steering tire life

[7] Tractor service life

The next components of VOC calibration are the highway characteristics. In order to compute VOC, one needs information of vehicle running speeds. Highway running speeds are a function of the desired speeds and a distribution (Weibull shape) factor, β, that combines the effects of terrain and road roughness. Table E- 4 shows the desired speeds, β, and the running speeds for seven types of vehicles. These desired and running speeds were estimated based on the 55 mph

speed limit. In sections where the speed limit has been changed to 65 mph, the figures in Table E- 4 may be slightly lower than reality. However, the running speeds shown in Table E- 4 closely approximate the speeds expected on uncongested highways in New York State (where 55 mph speed limits are imposed).

Table 4. Desired Speed Calibration Based on Canadian Data *(Adapted from BEIN[9])*

Vehicle Type	Payload [tons]	VDESIR, [mph]		β		Calculated Running Speed [mph][2]
		Assumed	HDM3 Default	Iterated	HDM3 Default	
Car	0.1 - 0.2	69	61.1	0.230	0.274	64.2
1/2- Ton	0.6	67	61.1	0.240	0.274	60.5
2-axle Truck	4.4	65	55.2	0.100	0.310	60.4
3-axle Truck	9.3	65	55.2	0.040	0.310	59.3
Bus	2.2	69	58.0	0.130	0.273	64.1
5-axle Truck	0.0	65	52.3	0.160	0.244	60.3
	11.4[1]	65	52.3	0.040	0.244	60.0
	25.4	65	52.3	0.040	0.244	50.6
7-axle Truck	0.0	65	52.3	0.220	0.244	60.3
	24.3[1]	65	52.3	0.040	0.244	60.5
	41.3	65	52.3	0.040	0.244	50.9

[1] Average network payload, including empties

[2] Based on Saskatchewan terrain

4.3.1 Economic versus Financial Costs

Vehicle Operating Costs (VOC) can be expressed as being either financial or economic. Financial costs are the actual accounting costs incurred by the various parties, while economic costs are financial costs minus market distortions such as taxes, duties, tariffs, subsidies, as well as external costs like pollution. The World Bank VOC models compute both financial cost and economic costs. Whether one uses economic costs or financial costs will depend on the type of cost analysis employed. At a planning level, economic costs are more appropriate to use because the policies resulting from such analyses reflect the best use of pure resources. On the other

hand, for budget planning, the costs must reflect true accounting costs, and financial costs should be used. In a pavement management system (PMS), VOC reduction due to maintenance activities are considered as benefits and the agency cost as costs. Since the same users of the system are incurring both user cost and agency cost (as tax payers), the most appropriate VOC to be used is the economic cost. If financial VOC costs are used in conjunction with agency costs we will be double-counting, for example, the tax portion of fuel cost that goes into highway maintenance.

However, in transferring models from Saskatchewan to New York State, it is safe to say that the financial cost part of the models may transfer better than the economic cost part. This is due to the lack of information at present about the Canadian tax burden on highway related commodities and how much of that burden is transferred to highway improvements. Models for both types of costs will be presented in this section.

4.3.2 User Delay Consideration in VOC Models.

Since the IRI range considered in these models includes that part where surface roughness starts to affect running speeds, the VOC models will be presented so that user cost that includes delay can be estimated. In situations where pavement surface is maintained, above say PSR 5, the delay part of VOC will be insignificant.

4.3.3 Saskatchewan VOC Models

The following model, adopted from the World Bank HDM3, was used in the Saskatchewan pavement management study:

$$VOC_i = \alpha_i \, e^{(A_i + B_i * IRI)} \qquad \text{...2}$$

Where, VOC_i = Vehicle operating cost for vehicle type i ($x10^{-1}$ 1986 CA ¢/km).

A_i and B_i = Calibrated constants for vehicle type i.

α_i = Administration cost factor for vehicle type i (commercial vehicles only)

IRI = International Roughness Index (m/km).

Table E- 5 shows the calibrated constants for the Saskatchewan VOC models.

Table 5 Calibrated Constants for the Vehicle Operating Cost Equations

	FINANCIAL COSTS					ECONOMIC COSTS				
		Excluding user delay		Including user delay			Excluding user delay		Including user delay	
Vehicle Type	α	A	B	A	B	α	A	B	A	B
Small Car	1.0	5.13	0.0256	5.77	0.0186	1.0	4.82	0.0265	5.45	0.0192
Medium Car	1.0	5.34	0.0260	5.88	0.0206	1.0	5.02	0.0272	5.56	0.0213
Large Car	1.0	5.52	0.0249	5.99	0.0196	1.0	5.20	0.0260	5.67	0.0203
½-ton	1.0	5.42	0.0298	5.96	0.0216	1.0	5.07	0.0320	5.62	0.0228
2-axle Truck	1.1	6.14	0.0564	-	-	1.1	5.79	0.0604	-	-
3-axle Truck	1.1	6.39	0.0394	-	-	1.1	6.04	0.0417	-	-
5-axle Truck	1.1	6.35	0.0343	-	-	1.1	5.98	0.0387	-	-
7-axle Truck	1.1	6.60	0.0421	-	-	1.1	6.24	0.0465	-	-
3-axle Bus	1.1	6.42	0.0236	7.67	0.0115	1.1	6.05	0.0250	7.33	0.0118

(Adapted from BEIN[9])

4.3.4 NYSDOT VOC Models

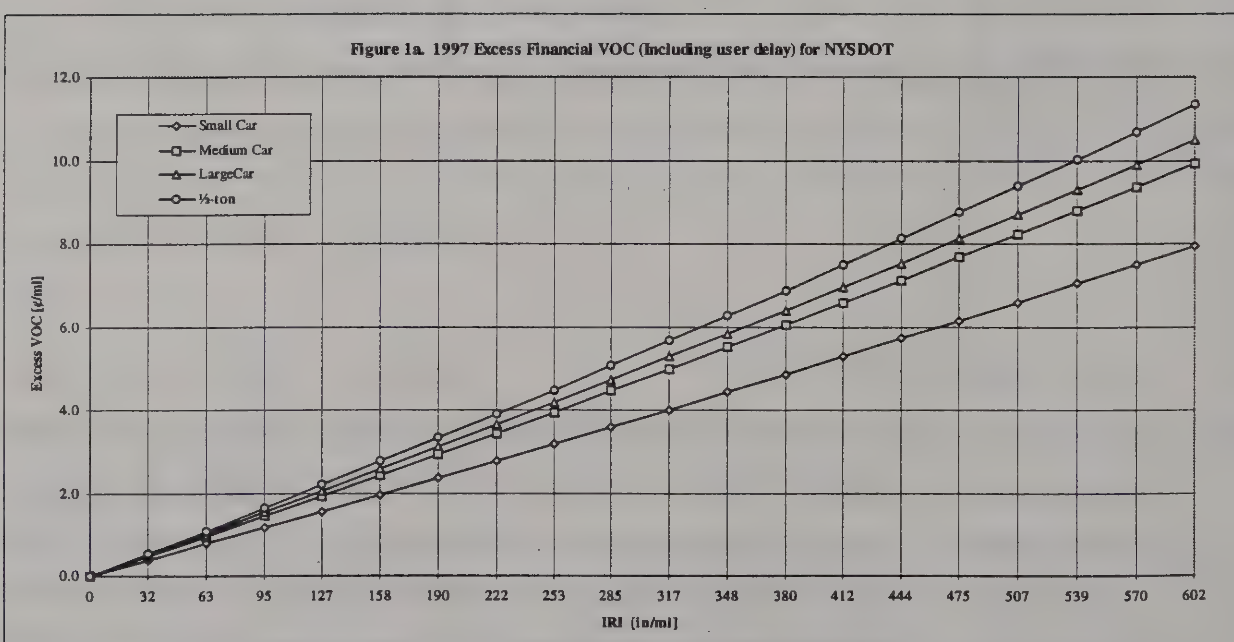
In order to convert the 1986 Canadian VOC figures to 1997 New York State VOC figures, a 5% inflation rate was assumed. This is consistent with NYSDOT directive, as discussed in the HUCA manual.[1] Also, a 1986 exchange rate of CA$1 to US$0.75 was assumed. Tables 1 to 4 in the Appendix present VOC figures that can be used by NYSDOT. Since it is often the case that only excess cost, rather than absolute value of VOC, is of interest, Figures E-1 to E-4 present this excess VOC. Excess VOC is the VOC users incur above what they would incur if the pavement allowed a perfectly smooth ride (IRI = 0). Tables 1 to 4 in the Appendix also show this excess cost.

To get a sense of what roughness (IRI) figures mean, Archondo-Callao and Faiz[8] suggest Table E- 6 that relate qualitative assessment of pavement roughness to the IRI scale.

Table 6. Qualitative Assessment of IRI

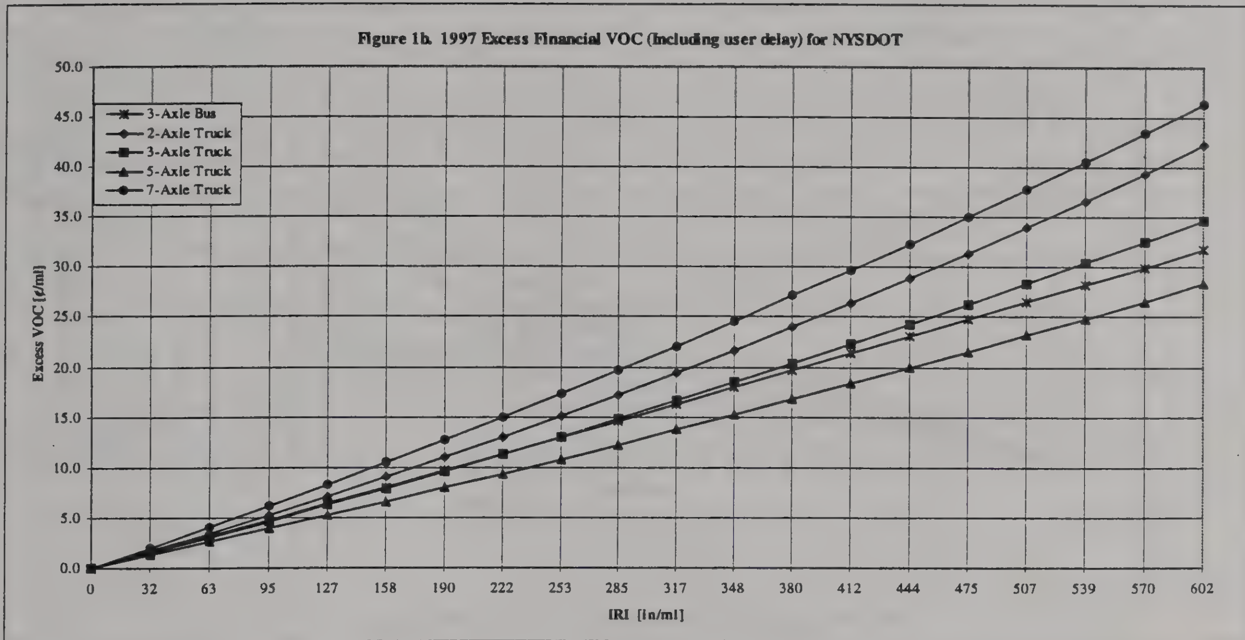
Qualitative Assessment	Pavement Roughness IRI [in/ml]		Possible PSR Values (paved)
	Paved Road	Unpaved Road	
Smooth	0 - 127	0 - 253	9, 10
Reasonably Smooth	127 - 253	253 - 507	7, 8
Medium Rough	253 - 380	507 - 760	5, 6
Rough	380 - 507	760 - 950	3, 4
Very Rough	507 - 634	950 - 1267	1, 2

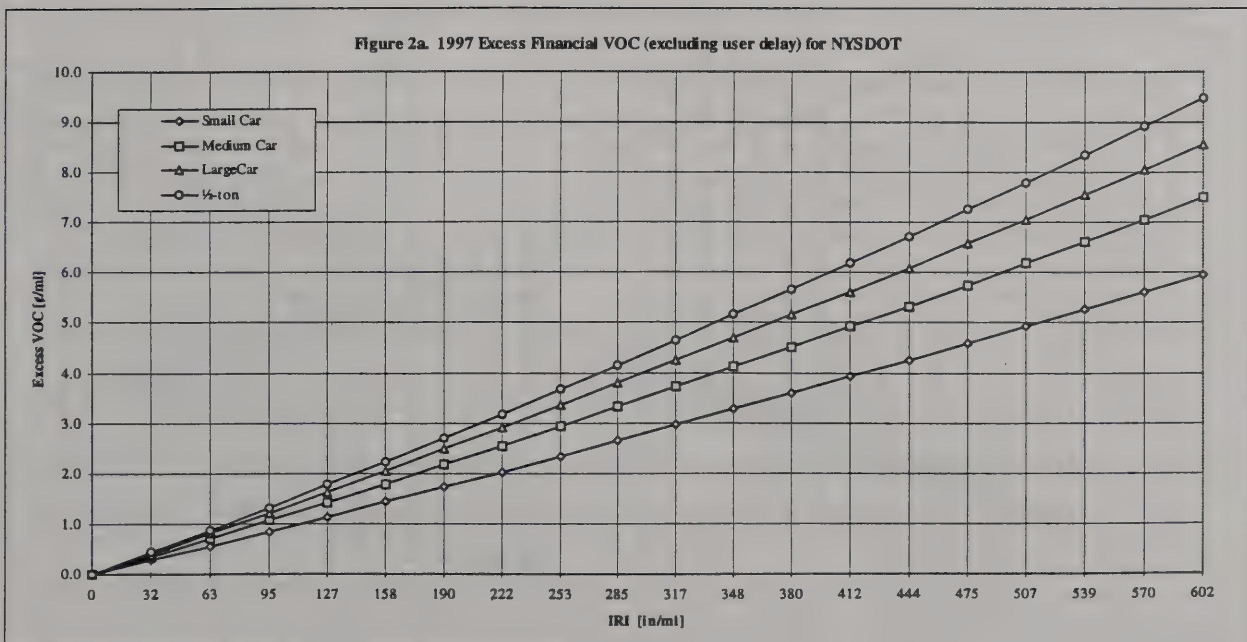
The last column of Table E- 6 is a "guesstimate" of equivalent PSR values. Those figures did not come from Archondo-Callao and Faiz.



Figures E-1(a & b) and E-2(a & b) show excess financial VOC that include and exclude user delay, respectively. They show, for example, that if pavements are left to deteriorate to IRI of 380, the average excess VOC for cars is 6 (¢/mi) if delay is included, and 4.5 (¢/mi) if delay is

excluded. On the other hand, Figures E-3 (a & b) and E-4 (a & b) show excess economic VOC as functions of IRI. If the pavement is left to deteriorate to IRI of 380, the average economic VOC for cars is 4.5 (¢/mi) if delay is included and 3.5 (¢/mi) if delay is excluded.





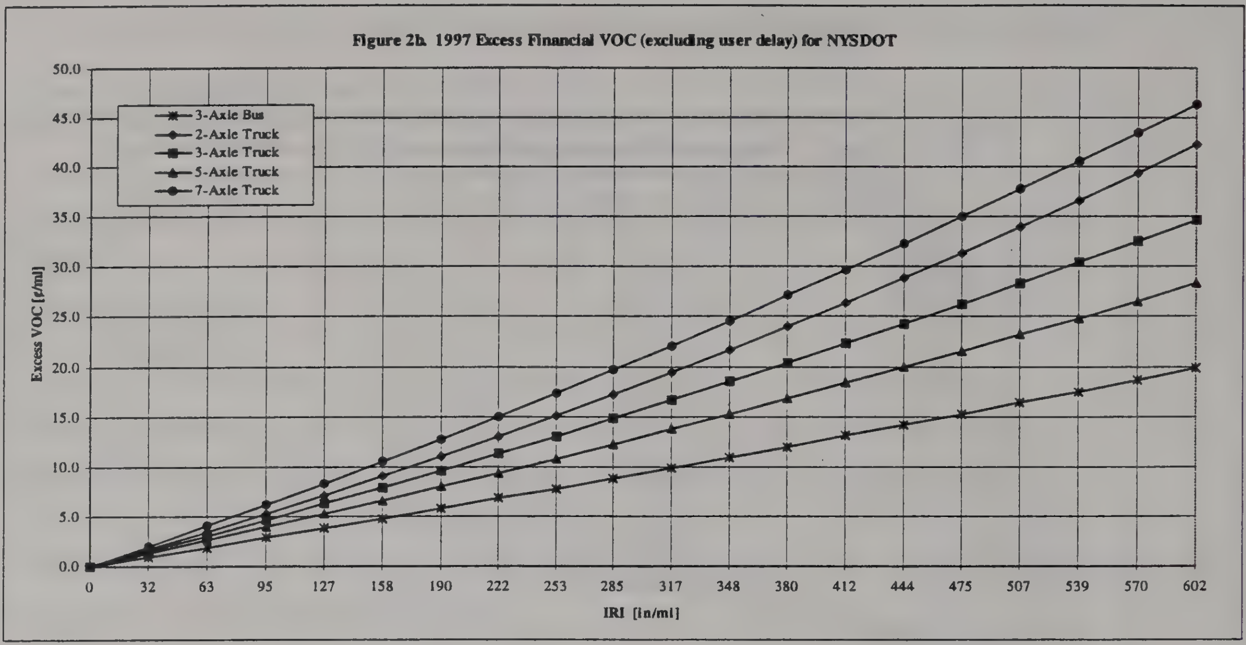


Figure 2b. 1997 Excess Financial VOC (excluding user delay) for NYSDOT
3-Axle Bus
2-Axle Truck
3-Axle Truck
5-Axle Truck
7-Axle Truck
Excess VOC [¢/mi]
IRI [in/mi]
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
0
32
63
95
127
158
190
222
253
285
317
348
380
412
444
475
507
539
570
602

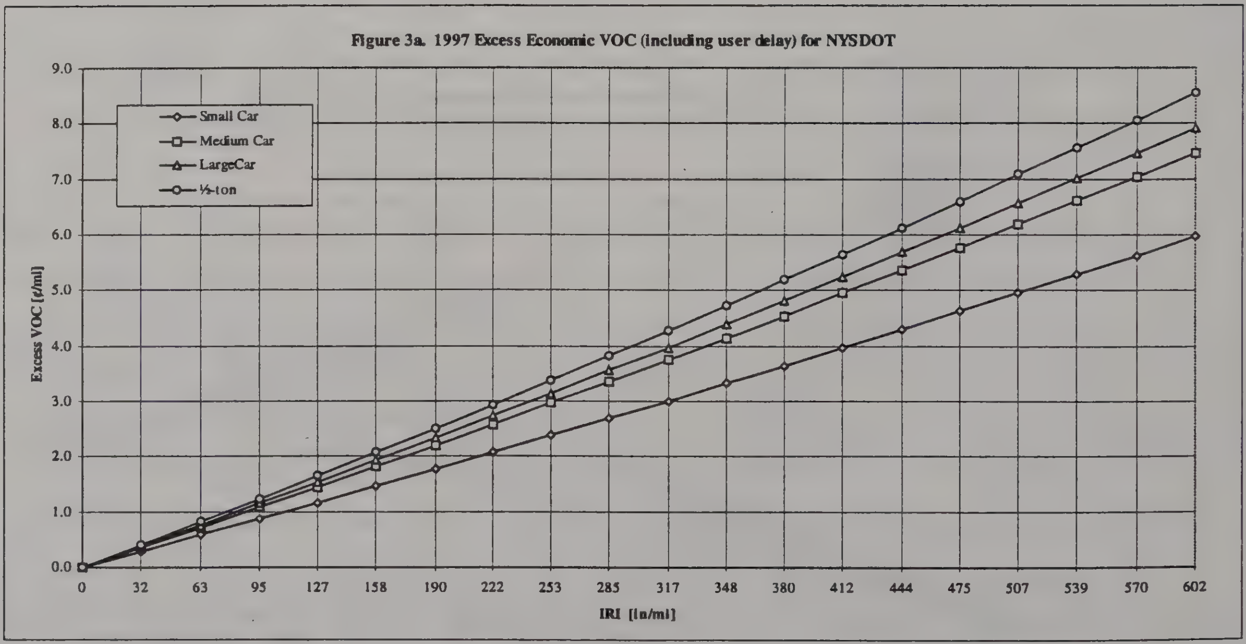


Figure 3a. 1997 Excess Economic VOC (including user delay) for NYSDOT
Small Car
Medium Car
LargeCar
½-ton
Excess VOC [¢/mi]
IRI [in/mi]
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
9.0
0
32
63
95
127
158
190
222
253
285
317
348
380
412
444
475
507
539
570
602

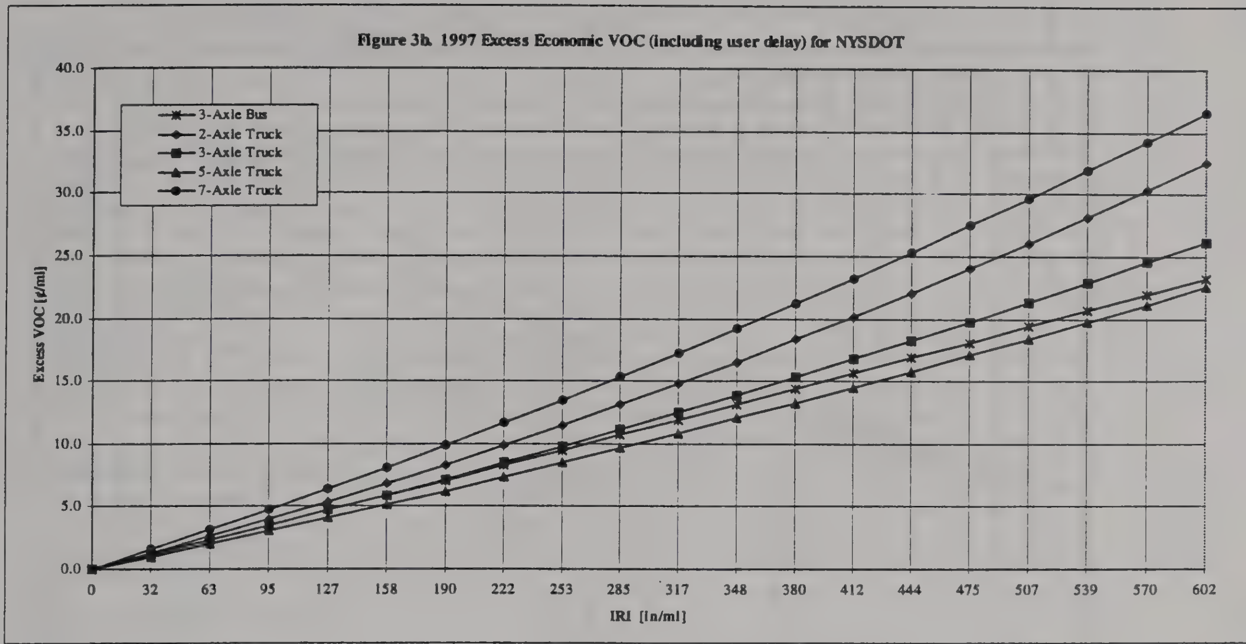


Figure 3b. 1997 Excess Economic VOC (including user delay) for NYSDOT
3-Axle Bus
2-Axle Truck
3-Axle Truck
5-Axle Truck
7-Axle Truck
Excess VOC [¢/mi]
IRI [in/mi]
0.0
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
0
32
63
95
127
158
190
222
253
285
317
348
380
412
444
475
507
539
570
602

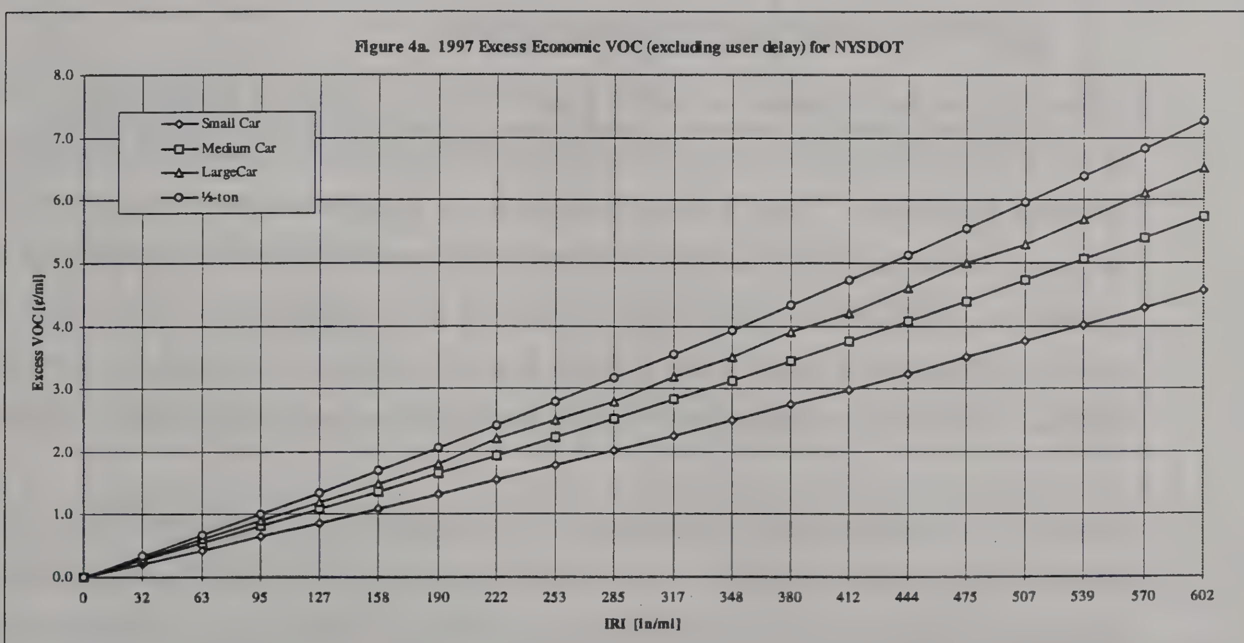


Figure 4a. 1997 Excess Economic VOC (excluding user delay) for NYSDOT
Small Car
Medium Car
LargeCar
½-ton
Excess VOC [¢/mi]
IRI [in/mi]
0.0
1.0
2.0
3.0
4.0
5.0
6.0
7.0
8.0
0
32
63
95
127
158
190
222
253
285
317
348
380
412
444
475
507
539
570
602

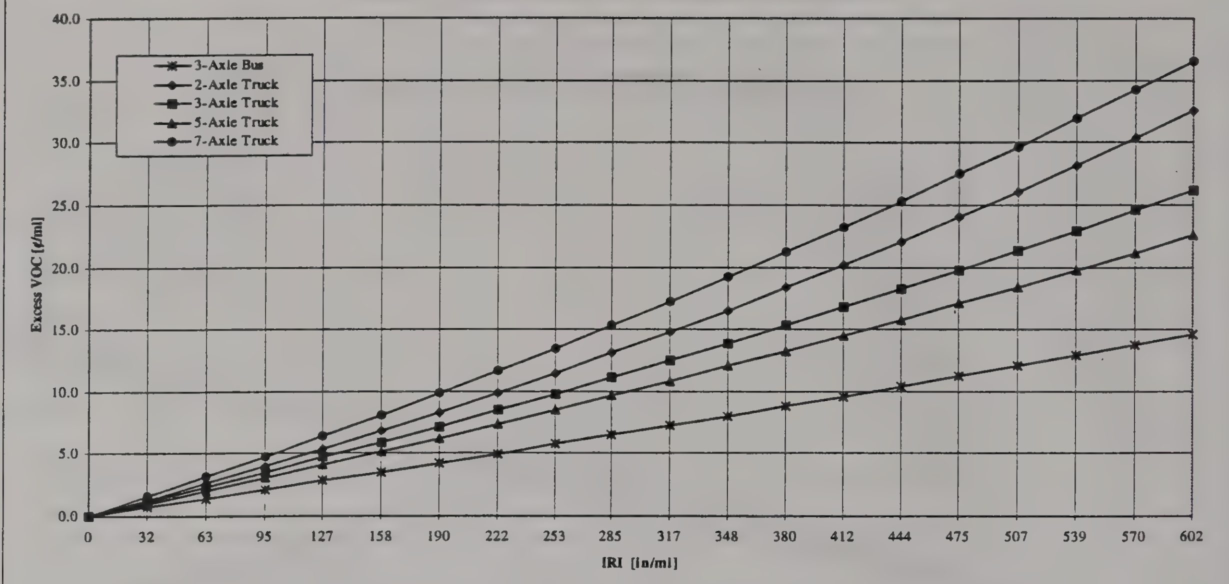


Figure 4b. 1997 Excess Economic VOC (excluding user delay) for NYSDOT

5. SUMMARY AND RECOMMENDATIONS

Tables 1 to 4 in the Appendix, as well as Figures E-1 to E-4, present recommended VOC values for NYSDOT. These VOC values are presented for individual vehicle types and are related to pavement roughness. There are four passenger car categories and five commercial vehicle categories. However, at the planning level traffic information is often not available at this level of details. Traffic data is often given in terms of total volume and percent trucks or heavy vehicles. Therefore, a useful form of VOC data is expressed as averages for cars and heavy vehicles. To do this, we need to know the distribution of cars and heavy vehicles on highways.

Table E- 7 below shows such information. This shows the distribution of heavy vehicles on highways and on urban facilities. It was compiled from the Port Authority of New York & New Jersey commodity surveys,[12] conducted between 1989 and 1992. We can deduce from Table E-7 that the average distribution of commercial vehicles on highways is 10% (2-axle), 5% (3 axle), and 85% (4+ axles). If we make a further assumption that passenger cars are distributed into 30% (small cars), 50% (medium cars), 15% (large cars) and 5% (½ ton), we can develop average VOC for cars and trucks from Tables 1 to 4 of the Appendix. Figures E-5 to E-8 are examples of such VOC curves, based on the distribution data assumed above.

Table 7. Distribution of Commercial Vehicles on New York Highways

Survey Location	Truck Distribution (%)			
	2 Axle	3 Axle	4+ Axle	Total
I-78[1]	9	2	89	100
I-80[1]	10	3	87	100
Bayonne Bridge[2]	49	14	37	100
Goethals Bridge[2]	28	9	63	100
George Washington (Lower) Bridge[2]	37	6	57	100
George Washington (Upper) Bridge[2]	19	7	74	100
Holland Tunnel[2]	70	10	20	100
Lincoln Tunnel[2]	77	50	17	100
Outer Bridge Crossing[2]	26	6	68	100
Midtown Tunnel[3]	88	7	4	100
Manhattan Bridge[3]	63	8	29	100
Queensboro Bridge[3]	87	6	7	100
Williamsburg Bridge[3]	72	9	19	100

[1] 1992 Truck-Commodity Survey[12]

[2] 1991 Truck-Commodity Survey[12]

[3] 1989 Truck-Commodity Survey[12]

Figure 5. 1997 Average Excess Financial VOC (including user delay) for NYSDOT

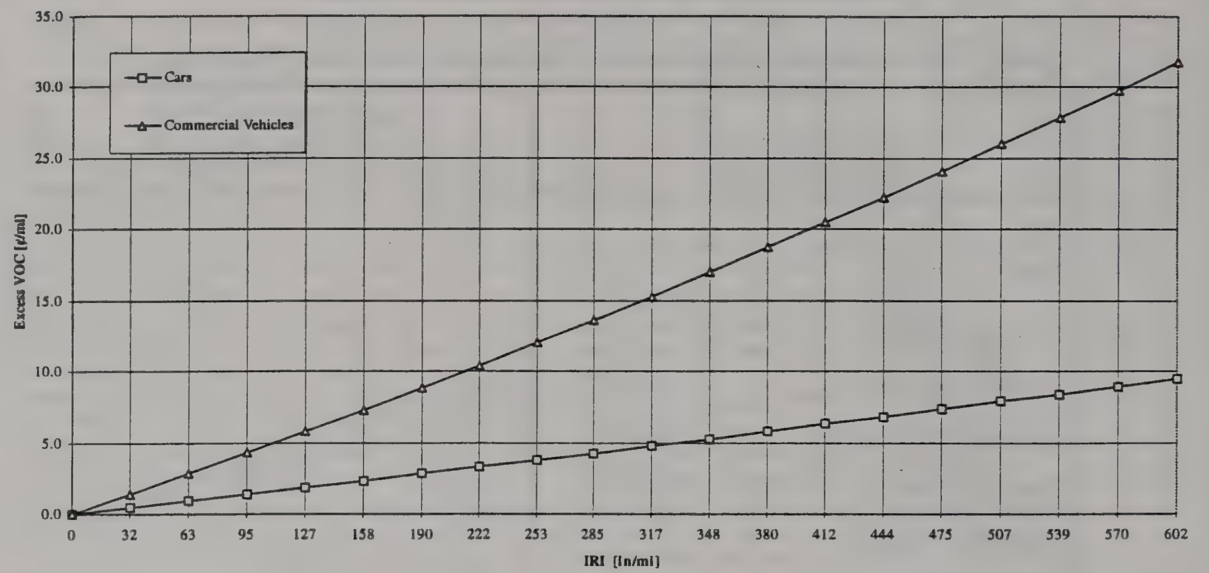
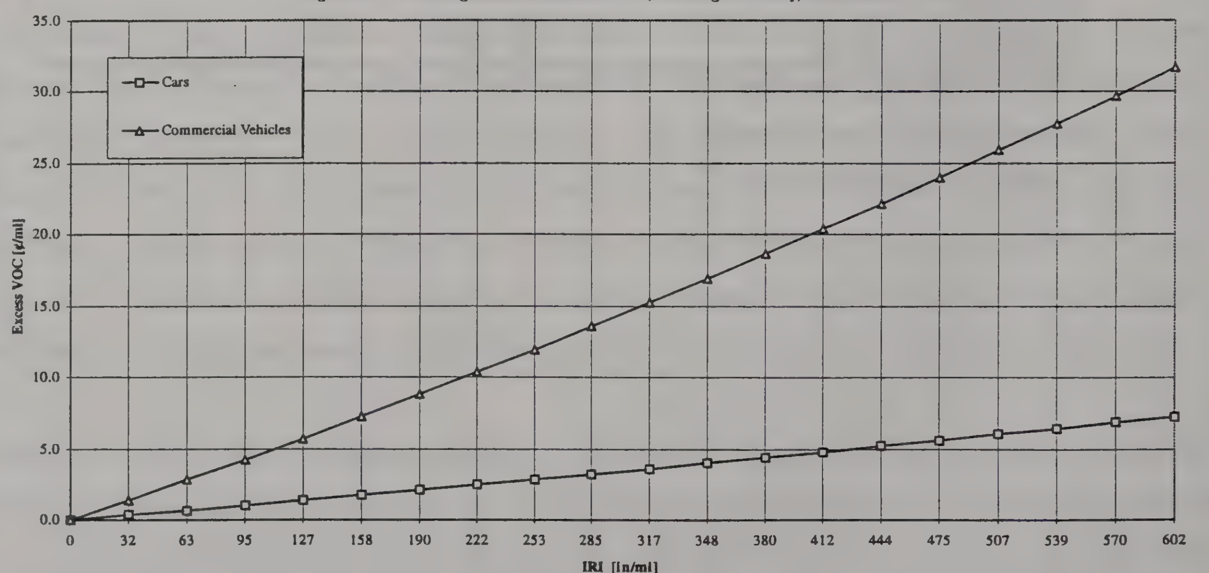


Figure 6. 1997 Average Excess Financial VOC (excluding user delay) for NYSDOT



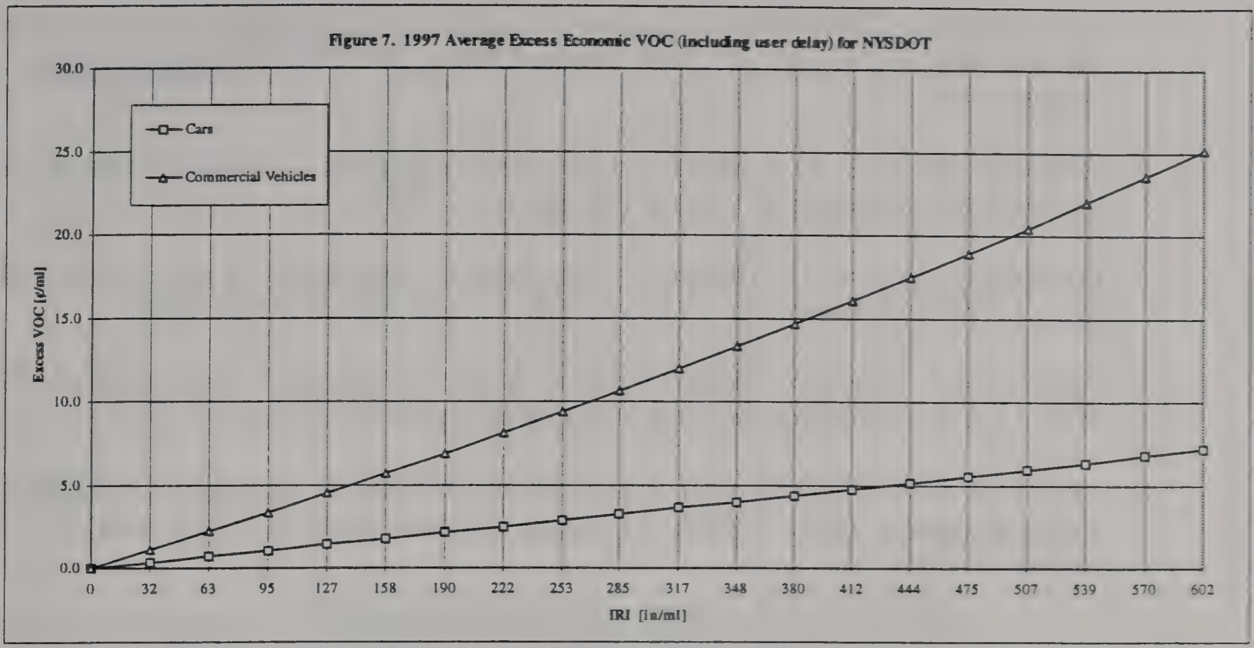


Figure 7. 1997 Average Excess Economic VOC (including user delay) for NYSDOT
Cars
Commercial Vehicles
Excess VOC [¢/mi]
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0
32
63
95
127
158
190
222
253
285
317
348
380
412
444
475
507
539
570
602
IRI [in/mi]

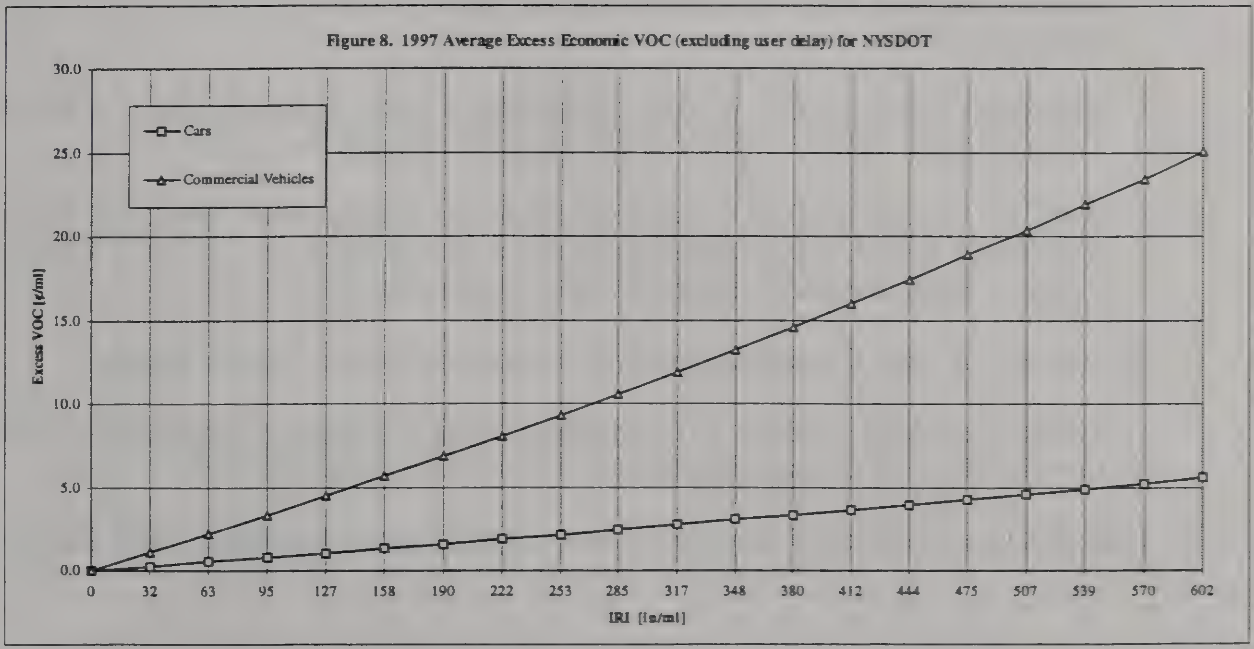


Figure 8. 1997 Average Excess Economic VOC (excluding user delay) for NYSDOT
Cars
Commercial Vehicles
Excess VOC [¢/mi]
30.0
25.0
20.0
15.0
10.0
5.0
0.0
0
32
63
95
127
158
190
222
253
285
317
348
380
412
444
475
507
539
570
602
IRI [in/mi]

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APPENDIX

Recommended VOC Tables for NYSDOT

Table A-1a. 1997 Financial User Costs for NYSDOT (including user delay) - [¢/mi][1]

Road Roughness (IRI)		CARS				COMMERCIAL VEHICLES				
		Small Car	Medium Car	Large Car	½-ton	3-Axle Bus	2-Axle Truck	3-Axle Truck	5-Axle Truck	7-Axle Truck
m/km	in/mi									
0.0	0	41.1	45.9	51.2	49.7	275.0	59.5	76.4	73.5	94.3
0.5	32	41.5	46.4	51.7	50.3	276.5	61.2	78.0	74.7	96.3
1.0	63	41.9	46.9	52.3	50.8	278.1	63.0	79.5	76.0	98.4
1.5	95	42.3	47.3	52.8	51.4	279.7	64.8	81.1	77.3	100.5
2.0	127	42.7	47.8	53.3	51.9	281.4	66.6	82.7	78.7	102.6
2.5	158	43.1	48.3	53.8	52.5	283.0	68.6	84.4	80.0	104.8
3.0	190	43.5	48.8	54.3	53.1	284.6	70.5	86.0	81.4	107.0
3.5	222	43.9	49.3	54.9	53.6	286.3	72.5	87.8	82.8	109.3
4.0	253	44.3	49.8	55.4	54.2	287.9	74.6	89.5	84.3	111.6
4.5	285	44.7	50.4	56.0	54.8	289.6	76.7	91.3	85.7	114.0
5.0	317	45.1	50.9	56.5	55.4	291.2	78.9	93.1	87.2	116.4
5.5	348	45.6	51.4	57.1	56.0	292.9	81.2	94.9	88.7	118.9
6.0	380	46.0	51.9	57.6	56.6	294.6	83.5	96.8	90.2	121.4
6.5	412	46.4	52.5	58.2	57.2	296.3	85.9	98.8	91.8	124.0
7.0	444	46.8	53.0	58.8	57.8	298.0	88.4	100.7	93.4	126.6
7.5	475	47.3	53.6	59.4	58.5	299.7	90.9	102.7	95.0	129.3
8.0	507	47.7	54.1	59.9	59.1	301.5	93.5	104.8	96.6	132.1
8.5	539	48.2	54.7	60.5	59.8	303.2	96.2	106.9	98.3	134.9
9.0	570	48.6	55.3	61.1	60.4	304.9	98.9	109.0	100.0	137.8
9.5	602	49.1	55.8	61.7	61.1	306.7	101.7	111.2	101.7	140.7
10.0	634	49.5	56.4	62.3	61.7	308.5	104.6	113.4	103.5	143.7
10.5	665	50.0	57.0	63.0	62.4	310.2	107.6	115.6	105.3	146.7
11.0	697	50.5	57.6	63.6	63.1	312.0	110.7	117.9	107.1	149.9
11.5	729	50.9	58.2	64.2	63.8	313.8	113.9	120.3	109.0	153.1
12.0	760	51.4	58.8	64.8	64.4	315.6	117.1	122.7	110.9	156.3
12.5	792	51.9	59.4	65.5	65.1	317.5	120.5	125.1	112.8	159.6
13.0	824	52.4	60.0	66.1	65.9	319.3	123.9	127.6	114.7	163.0
13.5	855	52.9	60.6	66.8	66.6	321.1	127.5	130.1	116.7	166.5
14.0	887	53.4	61.3	67.4	67.3	323.0	131.1	132.7	118.7	170.0
14.5	919	53.9	61.9	68.1	68.0	324.9	134.9	135.4	120.8	173.7
15.0	950	54.4	62.5	68.8	68.8	326.7	138.7	138.1	122.9	177.3

[1] Based on 1986 exchange rate of CA$1 to US$0.75 and an annual inflation rate of 5%

Table A-1b. 1997 Excess Financial User Cost for NYSDOT (including user delay) - [¢/ml]

Road Roughness (IRI)		C A R S				C O M M E C I A L V E H I C L E S				
m/km	in/ml	Small Car	Medium Car	Large Car	½-ton	3-Axle Bus	2-Axle Truck	3-Axle Truck	5-Axle Truck	7-Axle Truck
0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	32	0.4	0.5	0.5	0.5	1.6	1.7	1.5	1.3	2.0
1.0	63	0.8	1.0	1.0	1.1	3.2	3.5	3.1	2.6	4.1
1.5	95	1.2	1.4	1.5	1.6	4.8	5.3	4.7	3.9	6.1
2.0	127	1.6	1.9	2.0	2.2	6.4	7.1	6.3	5.2	8.3
2.5	158	2.0	2.4	2.6	2.8	8.0	9.0	7.9	6.6	10.5
3.0	190	2.4	2.9	3.1	3.3	9.7	11.0	9.6	8.0	12.7
3.5	222	2.8	3.4	3.6	3.9	11.3	13.0	11.3	9.4	15.0
4.0	253	3.2	3.9	4.2	4.5	12.9	15.1	13.0	10.8	17.3
4.5	285	3.6	4.5	4.7	5.1	14.6	17.2	14.8	12.3	19.7
5.0	317	4.0	5.0	5.3	5.7	16.3	19.4	16.6	13.7	22.1
5.5	348	4.4	5.5	5.8	6.3	18.0	21.7	18.5	15.2	24.6
6.0	380	4.9	6.0	6.4	6.9	19.6	24.0	20.4	16.8	27.1
6.5	412	5.3	6.6	7.0	7.5	21.3	26.4	22.3	18.3	29.7
7.0	444	5.7	7.1	7.5	8.1	23.0	28.8	24.3	19.9	32.3
7.5	475	6.2	7.7	8.1	8.7	24.8	31.3	26.3	21.5	35.0
8.0	507	6.6	8.2	8.7	9.4	26.5	33.9	28.3	23.2	37.8
8.5	539	7.0	8.8	9.3	10.0	28.2	36.6	30.4	24.9	40.6
9.0	570	7.5	9.4	9.9	10.7	30.0	39.4	32.5	26.6	43.4
9.5	602	7.9	9.9	10.5	11.3	31.7	42.2	34.7	28.3	46.4
10.0	634	8.4	10.5	11.1	12.0	33.5	45.1	36.9	30.1	49.4
10.5	665	8.9	11.1	11.7	12.7	35.3	48.1	39.2	31.8	52.4
11.0	697	9.3	11.7	12.3	13.3	37.1	51.2	41.5	33.7	55.5
11.5	729	9.8	12.3	13.0	14.0	38.9	54.3	43.8	35.5	58.7
12.0	760	10.3	12.9	13.6	14.7	40.7	57.6	46.2	37.4	62.0
12.5	792	10.8	13.5	14.2	15.4	42.5	61.0	48.7	39.3	65.3
13.0	824	11.2	14.1	14.9	16.1	44.3	64.4	51.1	41.3	68.7
13.5	855	11.7	14.7	15.5	16.8	46.2	67.9	53.7	43.3	72.2
14.0	887	12.2	15.3	16.2	17.6	48.0	71.6	56.3	45.3	75.7
14.5	919	12.7	16.0	16.8	18.3	49.9	75.3	58.9	47.3	79.3
15.0	950	13.2	16.6	17.5	19.0	51.8	79.2	61.6	49.4	83.0

Table A-2a. Recommended 1997 Financial User Costs for NYSDOT (excluding user delay) - [¢/ml][1]

Road Roughness (IRI)		CARS				COMMECIAL VEHICLES				
m/km	in/ml	Small Car	Medium Car	Large Car	½-ton	3-Axle Bus	2-Axle Truck	3-Axle Truck	5-Axle Truck	7-Axle Truck
0.0	0	21.7	26.8	32.0	29.0	78.8	59.5	76.4	73.5	94.3
0.5	32	22.0	27.1	32.4	29.4	79.7	61.2	78.0	74.7	96.3
1.0	63	22.2	27.5	32.8	29.9	80.7	63.0	79.5	76.0	98.4
1.5	95	22.5	27.8	33.2	30.3	81.6	64.8	81.1	77.3	100.5
2.0	127	22.8	28.2	33.7	30.8	82.6	66.6	82.7	78.7	102.6
2.5	158	23.1	28.5	34.1	31.2	83.6	68.6	84.4	80.0	104.8
3.0	190	23.4	28.9	34.5	31.7	84.6	70.5	86.0	81.4	107.0
3.5	222	23.7	29.3	34.9	32.2	85.6	72.5	87.8	82.8	109.3
4.0	253	24.0	29.7	35.4	32.6	86.6	74.6	89.5	84.3	111.6
4.5	285	24.3	30.1	35.8	33.1	87.6	76.7	91.3	85.7	114.0
5.0	317	24.6	30.5	36.3	33.6	88.6	78.9	93.1	87.2	116.4
5.5	348	25.0	30.9	36.7	34.1	89.7	81.2	94.9	88.7	118.9
6.0	380	25.3	31.3	37.2	34.7	90.8	83.5	96.8	90.2	121.4
6.5	412	25.6	31.7	37.7	35.2	91.8	85.9	98.8	91.8	124.0
7.0	444	25.9	32.1	38.1	35.7	92.9	88.4	100.7	93.4	126.6
7.5	475	26.3	32.5	38.6	36.2	94.0	90.9	102.7	95.0	129.3
8.0	507	26.6	32.9	39.1	36.8	95.1	93.5	104.8	96.6	132.1
8.5	539	27.0	33.4	39.6	37.3	96.3	96.2	106.9	98.3	134.9
9.0	570	27.3	33.8	40.1	37.9	97.4	98.9	109.0	100.0	137.8
9.5	602	27.7	34.2	40.6	38.5	98.6	101.7	111.2	101.7	140.7
10.0	634	28.0	34.7	41.1	39.0	99.7	104.6	113.4	103.5	143.7
10.5	665	28.4	35.1	41.6	39.6	100.9	107.6	115.6	105.3	146.7
11.0	697	28.7	35.6	42.1	40.2	102.1	110.7	117.9	107.1	149.9
11.5	729	29.1	36.1	42.6	40.8	103.3	113.9	120.3	109.0	153.1
12.0	760	29.5	36.5	43.2	41.4	104.6	117.1	122.7	110.9	156.3
12.5	792	29.9	37.0	43.7	42.1	105.8	120.5	125.1	112.8	159.6
13.0	824	30.2	37.5	44.3	42.7	107.1	123.9	127.6	114.7	163.0
13.5	855	30.6	38.0	44.8	43.3	108.3	127.5	130.1	116.7	166.5
14.0	887	31.0	38.5	45.4	44.0	109.6	131.1	132.7	118.7	170.0
14.5	919	31.4	39.0	46.0	44.6	110.9	134.9	135.4	120.8	173.7
15.0	950	31.8	39.5	46.5	45.3	112.2	138.7	138.1	122.9	177.3

[1] Based on 1986 exchange rate of CA$1 to US$0.75 and an annual inflation rate of 5%

Table A-2b. 1997 Excess Financial User Costs for NYSDOT (excluding user delay) - [¢/ml]

Road Roughness (IRI)		C A R S				C O M M E C I A L V E H I C L E S				
		Small	Medium	Large	½-ton	3-Axle	2-Axle	3-Axle	5-Axle	7-Axle
m/km	in/ml	Car	Car	Car		Bus	Truck	Truck	Truck	Truck
0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	32	0.3	0.4	0.4	0.4	0.9	1.7	1.5	1.3	2.0
1.0	63	0.6	0.7	0.8	0.9	1.9	3.5	3.1	2.6	4.1
1.5	95	0.8	1.1	1.2	1.3	2.8	5.3	4.7	3.9	6.1
2.0	127	1.1	1.4	1.6	1.8	3.8	7.1	6.3	5.2	8.3
2.5	158	1.4	1.8	2.1	2.2	4.8	9.0	7.9	6.6	10.5
3.0	190	1.7	2.2	2.5	2.7	5.8	11.0	9.6	8.0	12.7
3.5	222	2.0	2.5	2.9	3.2	6.8	13.0	11.3	9.4	15.0
4.0	253	2.3	2.9	3.4	3.7	7.8	15.1	13.0	10.8	17.3
4.5	285	2.6	3.3	3.8	4.2	8.8	17.2	14.8	12.3	19.7
5.0	317	3.0	3.7	4.2	4.7	9.9	19.4	16.6	13.7	22.1
5.5	348	3.3	4.1	4.7	5.2	10.9	21.7	18.5	15.2	24.6
6.0	380	3.6	4.5	5.2	5.7	12.0	24.0	20.4	16.8	27.1
6.5	412	3.9	4.9	5.6	6.2	13.1	26.4	22.3	18.3	29.7
7.0	444	4.3	5.3	6.1	6.7	14.2	28.8	24.3	19.9	32.3
7.5	475	4.6	5.8	6.6	7.3	15.3	31.3	26.3	21.5	35.0
8.0	507	4.9	6.2	7.1	7.8	16.4	33.9	28.3	23.2	37.8
8.5	539	5.3	6.6	7.5	8.4	17.5	36.6	30.4	24.9	40.6
9.0	570	5.6	7.1	8.0	8.9	18.6	39.4	32.5	26.6	43.4
9.5	602	6.0	7.5	8.5	9.5	19.8	42.2	34.7	28.3	46.4
10.0	634	6.3	7.9	9.1	10.1	21.0	45.1	36.9	30.1	49.4
10.5	665	6.7	8.4	9.6	10.6	22.2	48.1	39.2	31.8	52.4
11.0	697	7.1	8.9	10.1	11.2	23.4	51.2	41.5	33.7	55.5
11.5	729	7.4	9.3	10.6	11.8	24.6	54.3	43.8	35.5	58.7
12.0	760	7.8	9.8	11.2	12.5	25.8	57.6	46.2	37.4	62.0
12.5	792	8.2	10.3	11.7	13.1	27.0	61.0	48.7	39.3	65.3
13.0	824	8.6	10.8	12.2	13.7	28.3	64.4	51.1	41.3	68.7
13.5	855	9.0	11.2	12.8	14.4	29.6	67.9	53.7	43.3	72.2
14.0	887	9.3	11.7	13.4	15.0	30.8	71.6	56.3	45.3	75.7
14.5	919	9.7	12.2	13.9	15.7	32.1	75.3	58.9	47.3	79.3
15.0	950	10.2	12.8	14.5	16.3	33.5	79.2	61.6	49.4	83.0

Table A-3a. **Recommended 1997 Economic User Costs for NYSDOT (including user delay) - [¢/ml][1]**

Road Roughness (IRI)		CARS				COMMERCIAL VEHICLES				
m/km	in/ml	Small Car	Medium Car	Large Car	½-ton	3-Axle Bus	2-Axle Truck	3-Axle Truck	5-Axle Truck	7-Axle Truck
0.0	0	29.9	33.3	37.2	35.4	195.7	42.0	53.9	50.7	65.8
0.5	32	30.2	33.7	37.6	35.8	196.9	43.2	55.0	51.7	67.3
1.0	63	30.4	34.1	38.0	36.2	198.0	44.6	56.2	52.7	68.9
1.5	95	30.7	34.4	38.4	36.6	199.2	45.9	57.3	53.8	70.6
2.0	127	31.0	34.8	38.8	37.0	200.4	47.3	58.6	54.8	72.2
2.5	158	31.3	35.2	39.1	37.5	201.6	48.8	59.8	55.9	73.9
3.0	190	31.6	35.5	39.5	37.9	202.8	50.3	61.1	57.0	75.6
3.5	222	31.9	35.9	40.0	38.3	204.0	51.8	62.3	58.1	77.4
4.0	253	32.2	36.3	40.4	38.8	205.2	53.4	63.7	59.2	79.3
4.5	285	32.6	36.7	40.8	39.2	206.4	55.1	65.0	60.4	81.1
5.0	317	32.9	37.1	41.2	39.7	207.6	56.7	66.4	61.6	83.0
5.5	348	33.2	37.5	41.6	40.1	208.8	58.5	67.8	62.8	85.0
6.0	380	33.5	37.9	42.0	40.6	210.1	60.3	69.2	64.0	87.0
6.5	412	33.8	38.3	42.5	41.1	211.3	62.1	70.6	65.2	89.0
7.0	444	34.2	38.7	42.9	41.5	212.6	64.0	72.1	66.5	91.1
7.5	475	34.5	39.1	43.3	42.0	213.8	66.0	73.7	67.8	93.3
8.0	507	34.8	39.5	43.8	42.5	215.1	68.0	75.2	69.1	95.5
8.5	539	35.2	40.0	44.2	43.0	216.4	70.1	76.8	70.5	97.7
9.0	570	35.5	40.4	44.7	43.5	217.6	72.3	78.4	71.9	100.0
9.5	602	35.8	40.8	45.1	44.0	218.9	74.5	80.1	73.3	102.3
10.0	634	36.2	41.2	45.6	44.5	220.2	76.8	81.7	74.7	104.8
10.5	665	36.5	41.7	46.1	45.0	221.5	79.1	83.5	76.2	107.2
11.0	697	36.9	42.1	46.5	45.5	222.8	81.5	85.2	77.7	109.7
11.5	729	37.2	42.6	47.0	46.0	224.2	84.0	87.0	79.2	112.3
12.0	760	37.6	43.0	47.5	46.5	225.5	86.6	88.9	80.7	115.0
12.5	792	38.0	43.5	48.0	47.1	226.8	89.3	90.7	82.3	117.7
13.0	824	38.3	44.0	48.4	47.6	228.2	92.0	92.6	83.9	120.4
13.5	855	38.7	44.4	48.9	48.2	229.5	94.8	94.6	85.5	123.3
14.0	887	39.1	44.9	49.4	48.7	230.9	97.7	96.6	87.2	126.2
14.5	919	39.4	45.4	49.9	49.3	232.2	100.7	98.6	88.9	129.1
15.0	950	39.8	45.9	50.5	49.8	233.6	103.8	100.7	90.7	132.2

[1] Based on 1986 exchange rate of CA$1 to US$0.75 and an annual inflation rate of 5%

Table A-3b. 1997 Excess Economic User Costs for NYSDOT (including user delay) - [¢/ml][1]

Road Roughness (IRI)		CARS				COMMERCIAL VEHICLES				
m/km	in/ml	Small Car	Medium Car	Large Car	½-ton	3-Axle Bus	2-Axle Truck	3-Axle Truck	5-Axle Truck	7-Axle Truck
0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	32	0.3	0.4	0.4	0.4	1.2	1.3	1.1	1.0	1.5
1.0	63	0.6	0.7	0.8	0.8	2.3	2.6	2.3	2.0	3.1
1.5	95	0.9	1.1	1.2	1.2	3.5	4.0	3.5	3.0	4.8
2.0	127	1.2	1.5	1.5	1.7	4.7	5.4	4.7	4.1	6.4
2.5	158	1.5	1.8	1.9	2.1	5.9	6.8	5.9	5.2	8.1
3.0	190	1.8	2.2	2.3	2.5	7.1	8.3	7.2	6.2	9.9
3.5	222	2.1	2.6	2.7	2.9	8.3	9.9	8.5	7.4	11.6
4.0	253	2.4	3.0	3.1	3.4	9.5	11.5	9.8	8.5	13.5
4.5	285	2.7	3.4	3.6	3.8	10.7	13.1	11.1	9.7	15.3
5.0	317	3.0	3.7	4.0	4.3	11.9	14.8	12.5	10.8	17.2
5.5	348	3.3	4.1	4.4	4.7	13.1	16.5	13.9	12.0	19.2
6.0	380	3.6	4.5	4.8	5.2	14.4	18.3	15.3	13.3	21.2
6.5	412	4.0	5.0	5.2	5.7	15.6	20.2	16.8	14.5	23.2
7.0	444	4.3	5.4	5.7	6.1	16.9	22.1	18.3	15.8	25.3
7.5	475	4.6	5.8	6.1	6.6	18.1	24.0	19.8	17.1	27.5
8.0	507	5.0	6.2	6.6	7.1	19.4	26.1	21.3	18.4	29.7
8.5	539	5.3	6.6	7.0	7.6	20.6	28.2	22.9	19.8	31.9
9.0	570	5.6	7.0	7.5	8.1	21.9	30.3	24.5	21.1	34.2
9.5	602	6.0	7.5	7.9	8.6	23.2	32.5	26.2	22.5	36.5
10.0	634	6.3	7.9	8.4	9.1	24.5	34.8	27.9	24.0	39.0
10.5	665	6.7	8.4	8.8	9.6	25.8	37.2	29.6	25.4	41.4
11.0	697	7.0	8.8	9.3	10.1	27.1	39.6	31.4	26.9	43.9
11.5	729	7.4	9.3	9.8	10.6	28.4	42.1	33.2	28.4	46.5
12.0	760	7.7	9.7	10.3	11.1	29.8	44.7	35.0	30.0	49.2
12.5	792	8.1	10.2	10.7	11.7	31.1	47.3	36.9	31.6	51.9
13.0	824	8.5	10.6	11.2	12.2	32.4	50.0	38.8	33.2	54.6
13.5	855	8.8	11.1	11.7	12.8	33.8	52.9	40.7	34.8	57.5
14.0	887	9.2	11.6	12.2	13.3	35.2	55.8	42.7	36.5	60.4
14.5	919	9.6	12.1	12.7	13.9	36.5	58.8	44.7	38.2	63.3
15.0	950	10.0	12.5	13.2	14.4	37.9	61.9	46.8	39.9	66.4

Table A-4a. Recommended 1997 Economic User Costs for NYSDOT (excluding user delay) - [¢/ml][1]

Road Roughness (IRI)		CARS				COMMECIAL VEHICLES				
		Small	Medium	Large	½-ton	3-Axle	2-Axle	3-Axle	5-Axle	7-Axle
m/km	in/ml	Car	Car	Car		Bus	Truck	Truck	Truck	Truck
0.0	0	15.9	19.4	23.3	20.4	54.4	42.0	53.9	50.7	65.8
0.5	32	16.1	19.7	23.6	20.8	55.1	43.2	55.0	51.7	67.3
1.0	63	16.3	20.0	23.9	21.1	55.8	44.6	56.2	52.7	68.9
1.5	95	16.5	20.2	24.2	21.4	56.5	45.9	57.3	53.8	70.6
2.0	127	16.8	20.5	24.5	21.8	57.2	47.3	58.6	54.8	72.2
2.5	158	17.0	20.8	24.8	22.1	57.9	48.8	59.8	55.9	73.9
3.0	190	17.2	21.1	25.1	22.5	58.7	50.3	61.1	57.0	75.6
3.5	222	17.5	21.4	25.5	22.8	59.4	51.8	62.3	58.1	77.4
4.0	253	17.7	21.7	25.8	23.2	60.1	53.4	63.7	59.2	79.3
4.5	285	17.9	22.0	26.1	23.6	60.9	55.1	65.0	60.4	81.1
5.0	317	18.2	22.3	26.5	24.0	61.7	56.7	66.4	61.6	83.0
5.5	348	18.4	22.6	26.8	24.4	62.4	58.5	67.8	62.8	85.0
6.0	380	18.6	22.9	27.2	24.7	63.2	60.3	69.2	64.0	87.0
6.5	412	18.9	23.2	27.5	25.1	64.0	62.1	70.6	65.2	89.0
7.0	444	19.1	23.5	27.9	25.5	64.8	64.0	72.1	66.5	91.1
7.5	475	19.4	23.8	28.3	26.0	65.6	66.0	73.7	67.8	93.3
8.0	507	19.7	24.1	28.6	26.4	66.5	68.0	75.2	69.1	95.5
8.5	539	19.9	24.5	29.0	26.8	67.3	70.1	76.8	70.5	97.7
9.0	570	20.2	24.8	29.4	27.2	68.1	72.3	78.4	71.9	100.0
9.5	602	20.5	25.2	29.8	27.7	69.0	74.5	80.1	73.3	102.3
10.0	634	20.7	25.5	30.2	28.1	69.9	76.8	81.7	74.7	104.8
10.5	665	21.0	25.8	30.6	28.6	70.7	79.1	83.5	76.2	107.2
11.0	697	21.3	26.2	31.0	29.0	71.6	81.5	85.2	77.7	109.7
11.5	729	21.6	26.6	31.4	29.5	72.5	84.0	87.0	79.2	112.3
12.0	760	21.9	26.9	31.8	30.0	73.5	86.6	88.9	80.7	115.0
12.5	792	22.2	27.3	32.2	30.5	74.4	89.3	90.7	82.3	117.7
13.0	824	22.4	27.7	32.6	31.0	75.3	92.0	92.6	83.9	120.4
13.5	855	22.7	28.0	33.0	31.5	76.3	94.8	94.6	85.5	123.3
14.0	887	23.0	28.4	33.5	32.0	77.2	97.7	96.6	87.2	126.2
14.5	919	23.4	28.8	33.9	32.5	78.2	100.7	98.6	88.9	129.1
15.0	950	23.7	29.2	34.4	33.0	79.2	103.8	100.7	90.7	132.2

[1] Based on 1986 exchange rate of CA$1 to US$0.75 and an annual inflation rate of 5%

Table A-4b. 1997 Excess Economic User Costs for NYSDOT (excluding user delay) - [¢/ml][1]

Road Roughness (IRI)		CARS				COMMERCIAL VEHICLES				
m/km	in/ml	Small Car	Medium Car	Large Car	½-ton	3-Axle Bus	2-Axle Truck	3-Axle Truck	5-Axle Truck	7-Axle Truck
0.0	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
0.5	32	0.2	0.3	0.3	0.3	0.7	1.3	1.1	1.0	1.5
1.0	63	0.4	0.5	0.6	0.7	1.4	2.6	2.3	2.0	3.1
1.5	95	0.6	0.8	0.9	1.0	2.1	4.0	3.5	3.0	4.8
2.0	127	0.9	1.1	1.2	1.3	2.8	5.4	4.7	4.1	6.4
2.5	158	1.1	1.4	1.5	1.7	3.5	6.8	5.9	5.2	8.1
3.0	190	1.3	1.7	1.8	2.1	4.2	8.3	7.2	6.2	9.9
3.5	222	1.5	1.9	2.2	2.4	5.0	9.9	8.5	7.4	11.6
4.0	253	1.8	2.2	2.5	2.8	5.7	11.5	9.8	8.5	13.5
4.5	285	2.0	2.5	2.8	3.2	6.5	13.1	11.1	9.7	15.3
5.0	317	2.3	2.8	3.2	3.5	7.2	14.8	12.5	10.8	17.2
5.5	348	2.5	3.1	3.5	3.9	8.0	16.5	13.9	12.0	19.2
6.0	380	2.7	3.4	3.9	4.3	8.8	18.3	15.3	13.3	21.2
6.5	412	3.0	3.8	4.2	4.7	9.6	20.2	16.8	14.5	23.2
7.0	444	3.2	4.1	4.6	5.1	10.4	22.1	18.3	15.8	25.3
7.5	475	3.5	4.4	5.0	5.5	11.2	24.0	19.8	17.1	27.5
8.0	507	3.8	4.7	5.3	6.0	12.0	26.1	21.3	18.4	29.7
8.5	539	4.0	5.1	5.7	6.4	12.9	28.2	22.9	19.8	31.9
9.0	570	4.3	5.4	6.1	6.8	13.7	30.3	24.5	21.1	34.2
9.5	602	4.6	5.7	6.5	7.3	14.6	32.5	26.2	22.5	36.5
10.0	634	4.8	6.1	6.9	7.7	15.5	34.8	27.9	24.0	39.0
10.5	665	5.1	6.4	7.3	8.2	16.3	37.2	29.6	25.4	41.4
11.0	697	5.4	6.8	7.7	8.6	17.2	39.6	31.4	26.9	43.9
11.5	729	5.7	7.1	8.1	9.1	18.1	42.1	33.2	28.4	46.5
12.0	760	6.0	7.5	8.5	9.6	19.0	44.7	35.0	30.0	49.2
12.5	792	6.2	7.9	8.9	10.0	20.0	47.3	36.9	31.6	51.9
13.0	824	6.5	8.2	9.3	10.5	20.9	50.0	38.8	33.2	54.6
13.5	855	6.8	8.6	9.7	11.0	21.8	52.9	40.7	34.8	57.5
14.0	887	7.1	9.0	10.2	11.5	22.8	55.8	42.7	36.5	60.4
14.5	919	7.5	9.4	10.6	12.1	23.8	58.8	44.7	38.2	63.3
15.0	950	7.8	9.8	11.1	12.6	24.8	61.9	46.8	39.9	66.4